Sensors to Support the Soldier

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The charge, which was proposed by JASON itself and approved by Dr. Steve Lubard (Technical Director, S&T, ONR) read as follows:

"Ever in the vanguard of our nation's military forces, the Marine Corps must fight to secure the peace in nontraditional terrain, such as urban areas, often under restrictive rules of engagement. Such operations demand sophisticated sensors and surveillance so that threats may be countered with force appropriate to the environment. JASON will review ongoing programs and promising technologies that may meet these needs".

The JASON study focused on the following topic areas: squad-level communications; location, navigation, and maps; sensing through walls; countering snipers; and uses for UAVs. We will now summarize our principal findings and conclusions in each of these areas.

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Contents

1 EXECUTIVE SUMMARY

The JASON Summer Study on "Sensors to Support the Soldier" was conducted June 28 to July 30 2004 under the sponsorship of the Office of Naval Research. Paul Gido (Asst. Vice Chief of Naval Research, ONR) served as POC. The charge, which was proposed by JASON itself and approved by Dr. Steve Lubard (Technical Director, S&T, ONR) read as follows:

> Ever in the vanguard of our nation's military forces, the Marine Corps must fight to secure the peace in nontraditional terrain, such as urban areas, often under restrictive rules of engagement. Such operations demand sophisticated sensors and surveillance so that threats may be countered with force appropriate to the environment. JASON will review ongoing programs and promising technologies that may meet these needs.

As the study progressed, this rather broad task statement was refined and restricted in scope to focus on

- urban rather than open terrain;
- the needs of dismounted infantry;
- communications and ISR for immediate tactical use;
- near-term rather than visionary technologies.

These restrictions were motivated by the problems faced and the losses suffered by Marine forces currently engaged in Iraq, and by the desire to be useful quickly. However, the Marine's current problems are probably representative of those encountered in other urban operations of the past and future, so many of the technologies discussed in this report should be broadly applicable.

Relatively few formal briefings were conducted. Col. Len Blasiol (USMC, Director, Materiel Capabilities Division, MCCDC) spoke about "Marine Corps Future Military Operations in Urban Terrain." Dr. Bobby Junker (Head, ONR Code 31), discussed "ISR Initiatives and Persistent Surveillance." Randy Gangle (Executive Director, CETO) briefed JASON on lessons learned from Operation Iraqi Freedom [OIF] and OIF2. Jim McMains (ONR Code 353) briefed us on Unmanned Aerial Vehicles and also on the anti-sniper system Gunslinger. Barry Ketterer (Booz Allen Hamilton) briefed "Joint Perspective on ISR." Richard Carter (Joint Urban Operations Office & Oak Ridge National Lab) discussed Joint Force S&T Capabilities. Several participants in the study spent a day at the USMC urban-warfare training center at Camp Matilda in Riverside California. Fred McConnell of the Marine Corps Warfighting Lab was JASON's primary guide there and was extremely helpful. During our visit, we also received briefings by Major Dan Schmitt and other officers, and spoke informally with many other Marines, both instructors and trainees. We visited the Topographic Engineering Center at Fort Belvoir, Virginia, to be briefed on the Urban Tactical Planner and other digital maps by Joe Harrison. Additional information was received by telephone and electronic mail from numerous sources; we are particularly grateful to Susan Torfill (Marine Corps Systems Command) for information about tactical radios, and to Dr. Tony Tether (Director, DARPA) for briefing materials on related DARPA programs.

Most Marine infantrymen are issued little technologically sophisticated equipment for daytime missions. Normally there is only one military radio per squad of 13 men. The intent is to proliferate the Marconi Personal Role Radio down to the fire-team level (4 men) and even to the individual soldier, but this has yet to be fully accomplished. The infantry does not have organic vehicles, although urban patrols are often accompanied by vehicles attached to weapons companies. Consequently, the weight and electrical power of the infantry's gear is limited by the need to be man-portable.

The Marine infantryman relies on mobility, aggressiveness, and training

rather than elaborate equipment to accomplish his mission. JASON appreciates this philosophy and kept foremost in mind that the rifleman's mobility must not be hampered by heavy or power-hungry devices, nor should his natural senses be distracted from an awareness of his surroundings. Most of the technologies we discuss are augmentations of his natural senses, and they should provide information that can be immediately grasped and used.

The special challenges of urban warfare are well known. Lines of sight are restricted, both to the eye and to RF equipment, making communiations and coordinated maneuver difficult. GPS signals are often unavailable in high-rise districts and inside buildings. Structures provide good cover for adversaries, who usually know the area much better than our forces. The high density of geographic features demands smaller scale maps than the usual $1 : 50,000$ and unlike natural terrain—even mountainous areas—the landscape is not simply a two-dimensional surface but a fully three dimensional layering of multistory buildings, bridges, overpasses, *etc.* During low-intensity conflicts, such as the present one in Iraq, opposing forces may hide among noncombatants, and the rules of engagement may preclude large applications of force.

These challenges often demand warfighting tactics for which the Marines are not very well equipped or trained. JASON was told that while more than half of their engagements since the Korean War could be classified as urban, the Marines train only two weeks out of the year specifically for urban operations.

The JASON study focused on the following topic areas: squad-level communications; location, navigation, and maps; sensing through walls; countering snipers; and uses for UAVs. We will now summarize our principal findings and conclusions in each of these areas.

Our study finds that the most pressing technological need is a radio for every infantryman. While RF signals in the UHF to few-gigahertz range are scattered and attenuated by urban structures, they carry better than natural voice or visual signals. Although it is limited in range, is unencrypted, and

supports only voice communication, the Marconi Personal Role Radio has the advantages of simplicity, light weight, low power, and immediate availability. We hope that a PRR will soon be issued to every Marine rifleman. In the slightly longer term, COTS GSM cell phones, perhaps combined with COTS or non-COTS mobile base stations, could provide additional functionality, including encryption, non-voice data channels, hands-free operation, controllable access, and scalability to variable numbers of users. Also, modern cell phones carry sophisticated processors whose behavior might be modified to meet military needs by appropriate reprogramming in firmware. The base station is an important vulnerability, but these could be well protected (*e.g.* on armored vehicles or in UAVs) or sufficiently redundant. The risk of single-point (base-station) failure could be avoided by designing a modern military radio from scratch, but the design and development of such a radio might take years. The risk needs to be weighed against the advantage of immediate access to the latest developments in commercial technology.

We considered several approaches to location and navigation in the absence of conventional GPS guidance, including man-portable inertial measurement units, and digital imaging sensors combined with image processing and automated triangulation. However, by far the simplest approaches involve RF beacons of some sort. The commercial success of cordless and cell phones and 802.11 networks shows that walls and floors are not impenentrable to wireless signals; it is a question of power, range, and frequency. Conventional GPS transmitters send 50 Watts or less from ranges of $20,000\,\mathrm{km}$ or more, so that received powers are $\sim 10^{-16}\,\mathrm{W}$. A one-Watt transmitter at $\sim 1\,\mathrm{km}$ range, perhaps on a UAV or rooftop or ground vehicle, could deliver ~ 70 dB more power to ground level. This could allow usable signals to penetrate several concrete walls or floors. To be sure, nearby GPS beacons ("pseudolites") pose many technical challenges: geolocating the beacons well enough to support the desired $2-3\,\mathrm{m}$ system accuracy; multipath within structures and urban canyons; enormous variability in received signal strength; *etc.* But we believe that these challenges are superable. Alternative methods of RF geolocation might offer significant advantages over straight-

forward extensions of GPS: for example, transponders or synthetic aperture radars.

For some purposes, relative rather than absolute geolocation is adequate and might be obtained more easily. For example, if future radios were equipped to emit periodic ultra-wideband pulses or codes, these could be used as a transponder system to determine pairwise distances among members of a squad or fireteam without use of a pseudolite.

We recommend a technical study and perhaps a program of measurements to assess the viability of an RF-based deployable urban navigation system.

Digital maps of many urban areas of interest are available at resolutions of order one meter in the best cases, with limited three-dimensional information and annotation of significant structures. In particular, the Urban Tactical Planner [UTP] is unclassified, distributed by CD-ROM, and usable on laptops. The physical data come from many sources, including commercial satellite photography, airborne radars and lidars, and national technical means. Although obtained partly by image analysis, cultural data come largely from public documents and from human observation *in situ,* as does most data pertaining to interior or subterranean spaces.

Progress in the development of urban digital maps is impressive, but futher development will be needed before they are truly useful at the squad level in real time. The resolution of the imagery is often worse than the best current commercial standard (0.6 meter), and some areas are well imaged only once, so that stereoscopic measurements cannot be made nor shadows removed. Building heights are often estimated by counting windows rather than direct measurement. Cultural annotations are labor intensive and their error rate poorly quantified. There seems not to be a well-established protocol by which users report errors and updates, nor for those in theater to make their own digital annotations. Up-to-date maps are not available for all urban areas of interest: JASON was told that the UTP team has been tasked with 1500 cities, of which fewer than 100 have been completed, due

to limited staff and perhaps also limited data. Perhaps most importantly, a more portable and less distracting display than a laptop is needed for the dismounted soldier, especially in combat. At present, most infantrymen continue to make do with paper maps.

JASON examined technical options for tracking sniper fire. Prototypes based on various sensor modalities have been developed by several groups. A few have reached the field, including the tripod-mounted Metravib/PILARw passive-acoustic system and the VIPER UAV-borne IR system. We were briefed on the vehicle-borne Gunslinger system currently under development. To the best of our knowledge, no man-portable system has been fielded, and the Marine infantrymen rely upon their unaided hearing to determine the direction of fire: the slight time delay between the arrival of a sound at the soldier's two ears allows his nervous system to determine the angle of arrival. Unfortunately, the muzzle report is usually less audible than the shock cone, which arrives from a point on the bullet's trajectory rather than directly from the sniper's rifle.

In principle, the trajectory of the bullet can be reconstructed from the time of arrival of the shock alone at multiple, well-spaced, known locations, even without the muzzle report: this is the principle of the passive acoustic systems. In the 1990s, Bolt, Beranek, and Newman [BBN] developed a prototype of a man-wearable system involving helmet-mounted microphones and RF to communicate the arrival times; testing, though limited, indicated track errors $< 5^\circ$ in 90% of trials with 6 coordinated helmets. Passive acoustic systems are subject to errors due to winds, slowing of the bullet along its trajectory, and confusion if two or more shots occur in quick succession, but the unaided Marine is already subject to all of these errors and more. The ingredients can be cheap, not only in cost but also in weight and power: high-frequency (hence small) microphones, short-range RF communications at small data rates, and very modest computation. The hardest part is to know the locations of the microphones, but only relative locations are necessary if the system is carefully designed. All of these ingredients, except

perhaps for the microphones, could be synergistic with other applications, such as better radios and automatic navigation.

Another opportunity for inexpensive sniper-spotting is presented by the proliferation of cheap, compact, low-power imaging sensors, such as those now going into digital cameras and cell phones, to detect the muzzle flash at optical wavelengths. The chief challenge is achieve a high enough frame rate ($\sim$ kHz) to use the short rise time of the flash as a discriminant against other optical transients. We suggest two or three ways to do this, and we conclude that the flash should easily be detectable in daylight to a sensor mounted on or near the sniper's intended target, since the target necessarily has line-of-sight to the muzzle. Compared to passive acoustic systems, such optical systems have the disadvantage that the signal may not be detectable by soldiers other than the target, since they will lack a direct line of sight if the sniper has concealed himself well. On the other hand, an optical system need not know the soldier's position, since a still-frame picture could be used to designate the direction from which the flash was seen; such a picture could be comprehended by the soldier quickly and would be a natural byproduct of many optical sensing schemes. (Indeed, the PILARw and Gunslinger systems use a fast-slewing camera to designate the origin of the reconstructed bullet track.)

JASON also considered active-sonar and radar detection schemes. The former is probably not practical for a man-portable, power-limited system because of the low radiative efficiency of acoustic transducers in air. We estimate, however, that a man-portable, short-wavelength, bullet-tracking radar with an acceptable range ($\sim$ 100 m) and panoramic field of regard could weigh less than two pounds and consume a few Watts average of total electrical power, using helmet or vest-mounted microstrip arrays. Such a system could allow accurate track reconstruction from a single station or soldier, and with Doppler filtering it could have a negligible false-alarm rate. But such a radar would surely be more expensive to develop and deploy than the passive acoustic and optical approaches described above, and would

probably also be less economical of power. Like any active system, it would risk revealing soldiers' presence or location.

Based on these considerations, JASON recommends vigorous exploration and development of a hands-free, man-portable, sniper location system. Passive acoustic and optical systems are the most promising in the near term. Radar may be advantageous in the long term.

JASON was encouraged by some of our briefers, notably by some who have experienced urban combat, to study through-wall sensors. There are at least two primary motivations. The first is to detect people or movers in an adjoining room (or perhaps from greater standoff), and the second is to map the internal architecture of a building before entering it.

A number of portable RF systems have been developed to address the first requirement in the context of civilian applications such as search and rescue, hostage rescue, and the like. JASON did not receive briefings on any of these, but as far as we have been able to determine from public sources, most or all available systems are either too cumbersome or require too much time and deliberation to be practical for Marine infantrymen. There is a basic conflict between the low frequency needed for effective penetration of building materials (a few gigahertz at most) and the desire to obtain good spatial resolution with a small aperture. Motion can be detected by Doppler methods without spatial resolution and hence with a very small aperture; this is the principle of the Radar Flashlight developed at the Georgia Tech Research Institute, for example. But if the transmitter is moving, it is difficult to correct for self-induced Doppler shifts due to the velocity of the source relative to stationary objects, because these shifts vary with angle across the beam, which is broad if the aperture is small. Doppler systems work best if held still, which is often incompatible with the pace of combat. In principle, with the aid of an IMU attached to the transmitter, it might be possible to distinguish self-Doppler from target motion by SAR-like [Synthetic Aperture Radar] processing, but that may be difficult unless the motion of the transmitter, especially its attitude, is carefully controlled.

Instead, it may be possible to image the insides of buildings using a low-frequency airborne SAR, or at least the rooms closest to exterior walls; the two-way attenuation is of order $20 - 30$ dB at frequencies $\sim$ GHz. We have not discovered anyone who has tried to do this, but it would be an interesting experiment.

We point out that the internal architecture of buildings could be known if they were seen while under construction. For this reason and for the general purposes of urban mapping, frequent imaging of cities worldwide from orbit would be useful. This might be accomplished by purchasing commercial imagery (*e.g.* IKONOS, QuickBird): the available resolution ($\lesssim 1$ m) is already sufficient for mapping most buildings.

Unmanned aerial vehicles [UAVs] were not a specific focus of this JASON study, but we were encouraged by the progress made in developing such vehicles, especially the smaller and less expensive versions (such as Dragon Eye and Silver Fox) that might be available at the squad level. At present, most small UAVs carry electro-optical or IR imagers, but these vehicles could have many other uses in urban warfare: as communication relays, GPS pseudolites or other RF navigation beacons, as radar platforms, and as sniper spotters. During JASON's visit to Camp Matilda, we were told by a veteran of urban warfare that an aerial spotter can be invaluable to an infantry unit engaged in urban operations by warning them of nearby hostiles, calling in indirect fire, and generally serving as a "guardian angel." In the past this function has been performed by manned aircraft, but in the future it will increasingly be done with UAVs. However, even if bandwidth and heads-up displays permit, it might not be wise to send live video feeds routinely to troops on patrol, as it might be more of a distraction than a help. Instead, the imagery should probably be interpreted by an analyst in a safe location who distills and passes along information to the squad *in real time.* In order to further unburden combat troops from the duties of launching, controlling, and recovering their UAVs, while at the same time assuring the troops timely access to UAV services, JASON recommends consideration of

an aerial “taxi service” whereby a sufficient number of small UAVs would be kept in the air above the city at all times by ground crews operating from protected locations; these UAVs would follow squads on patrol or be summoned by them as needed.

To recap, the current technological level of the Marine infantry is rather basic. There is much that could be made available to them in the near term without elaborate development programs, as well as more futuristic technologies. JASON recommends that the near-term opportunities be emphasized, especially radios, passive sniper location systems, RF beacons, 3D maps, and small UAVs. Technological aids should be designed with these guiding principles in mind: they should be light in weight, low in power and cost, robust, and above all, they should do no harm to the Marine infantryman's immediate situational awareness. Finally, it will be better to give him a useful though imperfect system soon rather than await the development of a perfect system years hence.

2 COMMUNICATION

Communication among soldiers on the ground is extremely important. Current doctrine provides squad leaders with Marconi spread-spectrum radios, and platoon leaders with VHF radios. As a result, members of the squad or fire team must result to hand gestures and shouting in order to communicate.[1] We understand from our discussions with Marines, both officers and enlisted, that communication among the unit is one of the most important issues. This is made manifest by the fact that units have purchased commerical FRS (Family Radio Service) radios for use in Iraq. The risk imposed by using these radios is obvious, and we are not advocating them as a solution. We do recommend that every solder have a radio for communication with his unit, and that those communications be appropriately encrypted.

We begin (§2.1) by sketching a system that might be suitable for secure squad-level communications when every soldier is equipped with a radio moderately more sophisticated than the current Marconi Personal Role Radio (PRR). This system is not intended to scale gracefully to units much larger than a squad. It would require the development of new military radios, an effort that would not be technologically difficult but might delay deployment for a few years.

As an alternative, in §2.2 we propose the military use of commercial GSM cellphones and mobile base stations. Although perhaps not what one would design for the Marines on a clean sheet of paper, cell phones offer the latest commercial technology without the delay required to develop a specialized military radio.

[1] During an anti-sniper drill witnessed by JASON at Camp Matilda/March AFB on 7/9/04, unnecessary simulated casualties occurred because one Marine's report was not heard by the rest of his squad.

2.1 Security for Squad-level Radios

Since the intelligence value of intercepted communications among squad members is short-lived, elaborate security measures are not called for. A simple encryption scheme that uses encryption keys established when the squad is preparing for the mission could be used.

The question of who can use the radios and how the keys are established is interesting, and we provide a simple solution. First, establishing a set of keys could be done by the squad leader who enters a simple pass phrase into a key generation unit (which could be part of his radio). This pass phrase would be combined with some deterministic data such as the time of day, or with a pseudorandom source and the result passed through a cryptographic hash such as MD5 of SHA-1 [26] to generate a set of encryption keys. The issue of who may use a radio is important, especially if a soldier is wounded or his radio captured. Since all soldiers carry an indentification card with a chip embedded in it, and presumably this card also contains an RFID chip as well, then a system where the soldier places this card near his radio and then enters a PIN number as he would at at ATM machine would serve to authenticate the soldier to the radio. This action would be required to move to the next encryption key in the key set, which could be ordered when a radio is lost or a soldier has been wounded and there is a danger of his radio being captured.

An alternative approach that allows secure point-to-point communication is a simple Diffie-Helman key exchange. A Diffie-Helman key exchange proceeds with the initiator (A) choosing an integer base a, a prime p and a random integer x. A then computes the value $a^x \bmod p$ and sends a message to his communication partner B:

$$A \rightarrow B : a, p, [\![a^x \bmod p]\!].$$

Note that the value of $a^x \bmod p$ is sent and not the formula. B then chooses

a random integer y and responds

$$B \to A : [\![a^y \bmod p]\!].$$

A and B now share a key

$$k = [\![a^{xy} \bmod p]\!] = [\![a^{yx} \bmod p]\!].$$

A Diffie-Helman key exchange insures that the channel is secure, but it does not authenticate the participants. This should not be an issue since the soldiers in a unit know each other, and so they will know to whom they are talking.

We learned that communication is currently limited by the range of the VHF radios used by the platoon leaders. There are relay abilities in certain vehicles, but we learned that these are poorly understood and seldom used. The solution is to construct ad hoc communication networks. DARPA had the Global Mobile (GloMo) program in 1997–2000, and its developments should be considered. The technical issues centered around the hidden terminal problem, and floor access protocols, but these issues were addressed by the program and solutions were found.

2.2 Cell Phones for Soldiers

There is a need for a personal communication system to support individual soldiers, particularly for military operations in urban terrain (MOUT). One approach to provide this capability is the personal role radio (PRR) being developed by the Marines. The PRR provides push-to-talk (PTT) RF communication between individual soldiers and their squad leader.

The PRR uses a modified 802.11 format to provide non-secure voice over a direct sequence (DS) link that operates in the 2.4 GHz ISM band. An advantage of the PRR is that it requires no active infrastructure to support squad level communications. Because it uses DS spread spectrum (DSSS) it does provide a level of operational security (LPI) in spite of not using voice

encryption. DSSS also provides a level of anti-jam capability but that does not seem to be a requirement. The characteristics of the PRR are listed in Table 1.

Table 1: Characteristics of the Personal Role Radio.

Capability	**Criteria**
PRR Single Interface	System includes transceiver, headset, boom microphone, NBC respirator, push-to-talk (PTT) switch and carrying case.
PRR Dual Interface	Same system- *plus*-standard six-pin audio connector cable.
Voice	Provides nonsecure voice transmission with enough fidelity to allow identification of the speaker's voice.
Data Rate	None Required
Range	• 500 meters in rural terrain 200 meters • in urban terrain 100 meters in LAV • and AAV Five (5) rooms inside a • building Three (3) floors inside a • building.
Transmit Power	50mW
Frequency Rang	2.4 – 2.483 GHz. Industrial, Scientific and Medical (ISM) band.

An alternative to the PRR that might be considered is the use of COTS cell phones to provide squad level communications. The main disadvantage of COTS cell phones is that they require active infrastructure to support communications. To understand what is involved a discussion of cell phone technology is required. A typical commercial GSM cell phone system has several different components as shown in Figure 1.

The personal cell phone is referred to as the mobile station (MS). In GSM the MS includes a subscriber identity module (SIM) that contains information related to identity of the cell phone and its user for the purposes of billing. It provides a unique identifier to the possessor of the phone. The base transceiver system (BTS) contains the fixed transmitters/receivers and antennas and provides all communications to the MS. In general, several BTS are supported by the base station controller (BCS). In normal circumstances the mobile switching center (MSC) handles authentication as well

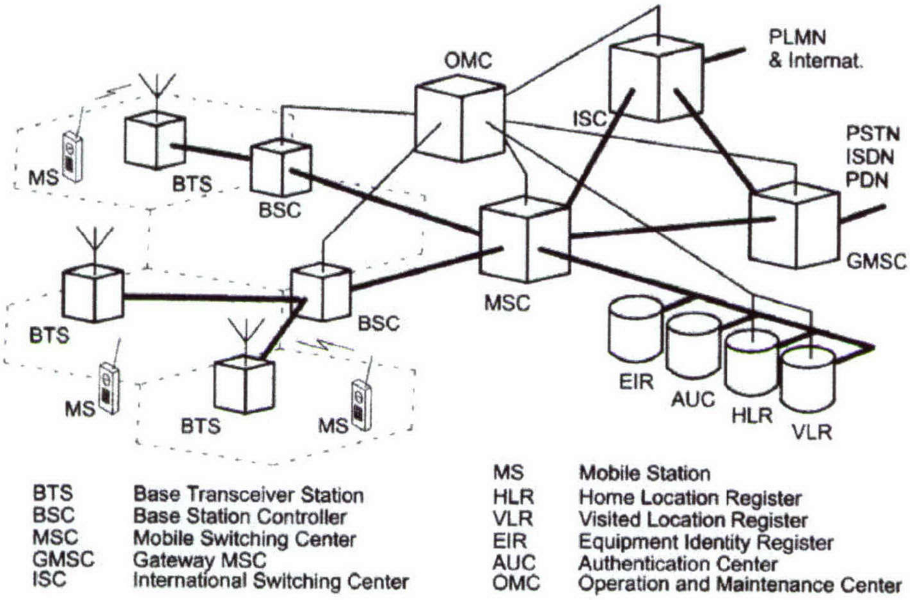

Figure 1: Components of a GSM cell phone network.

as switching and provides the connection into the land line communications system. Authentication is based on the MS SIM and databases containing authentication - the equipment identity register (EIC), home location register (HLR) and the authentication center database (AUC). Authentication provides a match between the SIM card and authorized equipment, users and subscribed services. For a COTS cell phone (MS) to work all of these components must be present in the supporting infrastructure. However, these components are available in a single package as COTs equipment. Figure 2 is interWave's Network-in-a Box (NIB) product that contains a BTC, BSC and MSC in a package the size of a PC tower.

For the purpose of providing squad level communications the NIB could be mounted in a HMMWV along with a suitable antenna.

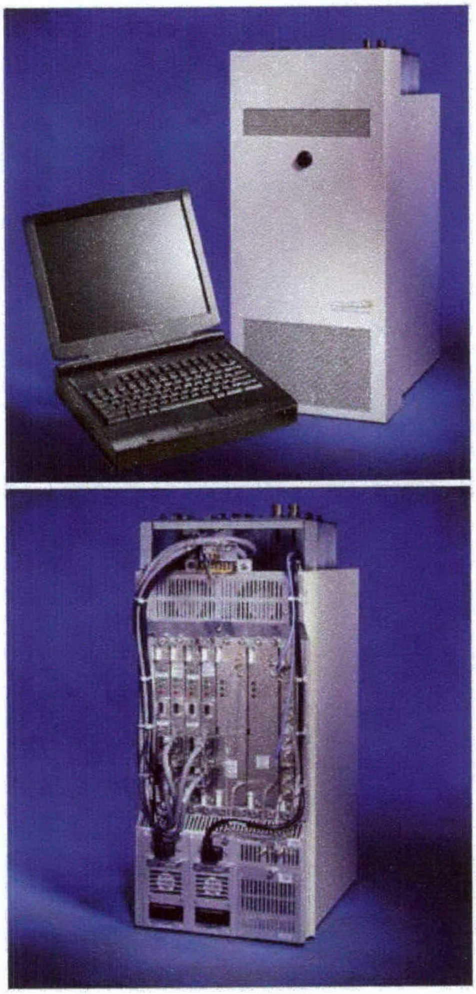

Figure 2: Network-in-a-Box

2.2.1 Comparison of PRR and COTs cell phone technology.

The PRR is designed specifically for the individual soldier and provides the capabilities required: short range push to talk voice conferencing with a degree of operational security, the latter via DSSS to allow low probability of intercept. The actual fielding of the PRR would go a long way in providing the individual soldier involved in MOUT a much needed capability. On the other hand the PRR is limited to voice only and therefore can not supply a

data connection to any of its users. The PRR is not a scalable system and can not be used to communicate over a wider area or within more broadly defined communities of interest, e.g. squad leader to platoon leader.

COTS cell phone technology is not specifically designed to support the individual soldier; however, it can offer most of the capabilities required in a scalable system that can provide services beyond voice and can more easily ride technology improvements.

- **Push to talk:** Nextel has offered PTT for a number of years and the capability can be provided in the GSM structure. In fact, PTT is now offered by some vendors in GSM phones.

- **Operational security:** GSM phones use frequency division multiple access (FDMA) and time division multiple access (TDMA) on the air interface but these were not specifically designed for LPI. The third generation of GSM (3G) also employs code division multiple access (CDMA) which will lower somewhat the probability of intercept. In addition GSM provides voice and data encryption that enhances operational security to a degree.

- **Communication discipline:** Each MS in GSM has a SIM that defines the user and contains data relevant to the allowed services on the MS. In addition the MSC databases can control the call behavior of the phone. Note that if the subscriber identity on the SIM does not match an international subscriber identity registered in the global GSM network the MS will not be able to connect into civilian GSM networks.

- **Data:** GSM supports the general packet radio service (GPRS) so that for suitably enabled devices data can be transferred. Thus using COTS cell phones both the individual voice needs of the soldier can be supported as well as possible data needs at the squad leader level and above.

- **Scalability:** Cell phone technology has been designed to allow scala-

bility in terms of numbers of users. Thus the same basic technology and be used to provide higher level communications and data transfers with an operational area. And in fact with a microwave or other connection into a rear, or central area, the same technology can allow higher level commanders to communicate to CONUS or other areas of operation.

While the use of COTS cell phone technology requires infrastructure to support the communication needs of the individual soldier there is flexibility in how that infrastructure is provided. As mentioned earlier the infrastructure could be provided on a HMMWV but also on semi-fixed towers, aerostats or even UAVs.

3 LOCATION

JASON has been told that the Marines have no fielded system for automatic reporting of the positions of individual infantrymen to their squad leaders, even when GPS or other location data are available. The squad leader relies upon vocal reporting *via* radio, or on visual contact. An automatic "blue-force" location system would improve situational awareness and allow the squad leader to better maneuver his troops. Equally importantly, it would relieve the individual infantryman of the distraction of having to report his position vocally—an advantage in stressful combat situations. One imagines that the squad leader could see his men displayed as moving dots superimposed on a map in a PDA or heads-up display.

Such a system must have (i) a means of geolocating the individual soldier, and (ii) a communications link, presumably RF. The latter is the easier component: there are of course power and LPI issues to be considered, but since the bandwidth needed for an automatic system is considerably smaller than that of a voice channel (a few tens of bits per report), these constraints are less severe than for the current procedure of verbal reporting. The hard part is accurate geolocation, especially in an urban environment. Buildings limit the line of sight, often rendering GPS useless. Members of a squad or even a fire team may lose visual contact over rather short distances, especially when inside buildings. These difficulties seriously degrade the Marines' ability to maneuver and concentrate their firepower in urban combat.

There are many technological possibilities for improving geolocation in urban environments. One class of solutions involves RF beacons of various kinds, such as high-power GPS pseudolites on UAVs to LORAN-like systems using ground-based transmitters. Such RF systems require additional infrastructure, which may be expensive and vulnerable to the enemy, but the infantryman could use them with relatively little weight and power invested in receivers, electronics, and batteries. We will discuss some options along these lines.

At the other extreme are methods that require little or no infrastructure but require more complex instrumentation on the soldier. In general, these approaches are "sportier," *i.e.,* involve greater technical risk. The good news is that weight and power can often be traded for data storage and computation, where progress is rapid because of technological opportunities and commercial demand, as demonstrated by the rapidly increasing functionality of cell phones and PDAs, for example. Unfortunately, despite intense commercial interest, batteries and other portable energy sources have improved only slowly. Evidently, energy storage is an intrinsically harder problem.

3.1 GPS

It is clear that Blue Force position tracking is desirable, so long as that information can be restricted. The need for GPS or GPS-like functionality at the individual solider level is demonstrated by the large number of soliders who on their own have bought commericial GPS units for use in Iraq.

The commerical availability of integrated GPS and FRS/GMRS devices such as the Garmin Rino [25, 13] demonstrate that such devices using GPS technology can be made inexpensively. The Garmin Rino is an FRS (Family Radio Service) operating at 500 mW, 462.5625–467.7125 MHz and GMRS (General Mobile Radio Service) operating at 1W, 550–462.725 MHz with an integrated GPS unit. It allows users to report their position and map the position of other users up to a range of about 2 miles. The advantage of such a system at the squad or platoon level are clear: knowing the position of individual fire team members can greatly reduce friendly fire casualties and aid in coordinated action. The disadvantage is also clear: the adversary could also know their position.

It would be a simple matter to include type 2 encryption in such a device. The positions of individual soldiers are likely to change rapidly, and the

time to decrypt positions using a type 2 cipher such as AES [1] would greatly exceed the duration of their utility even for a very sophisticated state-level adversary.

3.2 Augmented GPS

For the soldier on the ground in a urban environment GPS often has limited utility due to its weak signal which is attenuated by building walls and by the urban canyons of cities.

Previously, JASON was asked to explore non-GPS methods of geolocation [5]. One method mentioned was the use of GPS pseudolites. Traditionally GPS pseudolites have been proposed for large expensive platforms, such as satellites or manned reconnaissance aircraft that are capable of theaterwide coverage. But GPS pseudolites could be deployed on smaller, less expensive platforms as well as on other assets that might be in theatre, with less coverage, ranging down to squad or company deployment areas. For example, in Iraq we are informed that several aerostats have been deployed. Placing a 10W GPS pseudolite on each of these would provide a signal 60 dB stronger than the signal from the GPS satellites, assuming a distance to satellite of 26000 km, distance to aerostat of 10 km and a satellite power of 50 W. If the pseoduolite were placed on a UAV at 1 km, then an additional 20 dB would be gained. At 1.6 Ghz, penetration of one foot of building concrete reduces the signal by[2] 16 dB (perhaps more with rebar, pipes and other metal structures), but given that we have gained 60–80 dB over the satellite, getting a signal inside the building should be no longer be difficult.

GPS pseudolites could also be deployed either on dedicated small UAVs; on small UAV L-band SARs (§3.3); or they could piggyback on larger UAVs (Predator-A) used as pseudolites of opportunity when in the area. Predator-

[2]This is based on the dielectric constant $\epsilon = 7+0.85i$ recommended by the International Telecommunication Union [24] and assumes normal incidence; at 60° from the normal, the loss increases to $21-25$ dB depending on polarization. According to the ITU, considerably less loss occurs through interior walls and floors.

A UAVs could easily carry the pseudolite electronics with little power or weight penalty in comparison with their overall capacities (200 kg payload, prime power of 75 kW). A potentially suitable small UAV is the Silver Fox; we describe in more detail its dual use for both L-band SAR and as pseudolite in §6. Even smaller than the Silver Fox is Dragon Eye; it could provide an interesting opportunity but it has quite small payload power and weight. Small UAVs are relatively inexpensive (and we believe could be made much more inexpensive), and light enough to be readily transported into hostile territory (the Dragon Eye and equipment can be man-carried). The Silver Fox, weighing 10 kg with a wingspan of 2.7 m, has a 1.8 kg payload and a flight endurance of 10 hours (expected to be increased to 20 hours). With a dedicated payload, Silver Fox UAVs could be used as GPS pseudolites working on battery power of about 3 W. They would track their own position using GPS, and since their antenna could be on the top and shielded, and since they could fly at about 300 m they should be less susceptible to jamming. The Dragon Eyes are even smaller and lighter UAVs (2.3 kg, 1.1 m wingspan) having a flight time of about an hour and a battery-powered payload of half a kilogram. It is not clear to us that a pseudolite payload could be made small enough to fit on the Dragon Eye, but it is worth investigating.

Inertial navigation systems that are light enough to be carried by a soldier already heavily loaded with gear will lose GPS-level accuracy in a matter of minutes [5]. This does not mean that they lack utility (§3.4). MEMS-based accelerometers with less than 1mg sensitivity have been developed, and commerical devices with less than 2mg sensitivity and a $300\mu g/\sqrt{\mathrm{Hz}}$ noise floor are commonly available. Such devices could be used to fill in the gaps between GPS fixes or other location techniques.

3.3 Other RF Methods

If pseudolites are used as direct imitators of the GPS satellite constellation, a real problem is that at least four pseudolites are needed to provide ge-

olocation. But there are other ways of making use of assets such as UAVs that are capable of transmitting RF at modest power levels, and these techniques can (with some loss of geolocation utility, such as geolocation in only two dimensions instead of three) reduce the number of UAVs needed for geolocation down to a single one. Moreover, these pseudolites need not be dedicated solely to geolocation function, but may have dual use as SARs (described in §6. As above, we are concerned with indoor geolocation and restrict our attention to ultrawide-band precision location (UWBPL) in L band. This band is chosen because of the good compromise between penetration of walls and ceilings (favoring low frequency) and size of antennas suitable for small UAVs and the like (favoring high frequency). The ultrawide-band (UWB) feature is essential to reduce indoor multipath, since the time duration of a pulse is much less than the time duration associated with typical indoors multipath.

The first method we discuss is somewhat similar to ordinary GPS but without the need for clocks that are precise and stable over long times; it uses four equivalents of pseudolites. It is a development of research originally funded by DARPA and is in the process of being commercialized by Multispectral Solutions, Inc. There may well be other commercial geolocation systems of this type that we have not run down in our summer study.

The Multispectral UWBPL system yields 3-D locations inside and outside buildings from precision time-of-arrival measurements. The system employs a transmitter/receiver, called the rover, whose location is needed. The rover emits a sequence of pulses centered at 1.5 GHz with a bandwidth of 400 MHz (2.5 nanosec duration), with a pulse repetition frequency of 100 Hz. These pulses, which contain the rover's identification, are received by (usually) four beacons, each of which transponds a signal to the rover. The rover, which knows the positions of the beacons, determines its position from the four pseudoranges. The leading edges of the pulses can be detected for sub-nanosec (subfoot, spatially) resolution. The system range is about 2 km outdoors, and perhaps 100 m indoors depending on wall type. The system is

useful indoors for wall attenuation (reflection and absorption) of about 25 dB, according to Multispectral Solutions. Commercial applications of UWBPL envisage rovers and beacons in a cooperative building, but there may nevertheless be uses in urban warfare. Beacons can be placed on external building walls in known locations, either man-placed or by some sort of slow-speed launcher launching a beacon with something added so it can stick to the side of a building.

In §6 we point out that the Multispectral parameters are actually suitable for use in small-UAV SARs. This does not mean that the actual Multispectral hardware can be trivially converted to SAR function, but it is an indication that it should not be terribly difficult to devise similar hardware that would work well for SAR. These SARs can be used in various ways for geolocation (as well as for SAR function).

The first way is the classical pseudolite solution, with four UAVs. These receive GPS data and determine their own position. The transmitted SAR signals are encoded with the UAV position and GPS time. Even with only a few watts of power they would be some 90 dB stronger, at 1 km range, than the GPS satellite signal. Since the radiated signals actually encompass the usual GPS bands, it is possible that conventional GPS receivers could be modified relatively simply, either in software or processor hardware, to handle the signals from the SARs.

The number of UAVs needed for geolocation can be reduced to three with conventional pseudolite operation simply by accepting location in two dimensions. In the urban setting, this will often suffice, given decent topographical maps of the area, since the soldier requesting geolocation indoors will probably know what floor he is on. But a better way to use three UAVs gives full 3-D location. Those requesting geolocation will have transponders that repeat the SAR pulses (coded for identification) back to the SARs, with known time delays; the SARs compute the ranges to the requester and relay them. The requester then computes his geolocation. Clock accuracy and stability is required only on the time scale of SAR coherent processing, which

is a few seconds. The transponders are strong enough to give signals at the SAR that are many dB above the general returns making up the SAR image data.

The above methods make no use of Doppler, but since we envision the geolocator UAV as functioning as a SAR, we should take advantage of this extra modality. By so doing, the number of UAVs needed for 3-D geolocation can be reduced to two. It is necessary that the transponder of the geolocation requester be able to repeat the SAR signal accurately on the scale of Doppler shifts from SAR motion, which are a few tens of Hz. Two UAVs can then determine the full 3-D position.

Finally, if 2-D position is good enough, a single SAR on a UAV can give this by the techniques of the above paragraph.

3.4 Inertial Navigation

A perfect inertial measurment unit (IMU) could be very handy inside buildings. The most basic use, which does not require previous knowledge of the internal layout, would be to retrace one's steps to get out of the building: especially when in haste and under stress, a soldier could otherwise very easily get lost inside a large structure. A more advanced use could be to guide the Marine toward a target whose position had been determined from outside, *e.g.,* a room from which a sniper was firing. With very modest RF bandwidth, IMUs could allow several Marines to know their relative locations inside the building.

MEMs technology has enabled very lightweight and low-power IMU systems. Most commercially available systems have unacceptably large errors, unfortunately. The drift rate is determined by the noise levels of the accelerometers and gyros[3], which are typically $\sigma_a \approx 10^{-3}\,\mathrm{m\ s^{-2}\,Hz^{-1/2}} = 1\mathrm{mg\,Hz^{-1/2}}$ and $\sigma_g \approx 10^{-2}\mathrm{deg\ s^{-1}\,Hz^{-1/2}}$. The position error due to the

[3]For the moment we neglect errors caused by unknown biases (DC offsets) in the sensors.

accelerometers alone, assuming perfect gyros, grows with time as

$$\langle \Delta x(t)^2 \rangle^{1/2} = \left(\frac{\sigma^2 t^3}{6} \right)^{1/2} \approx 2. \left(\frac{t}{1\,\mathrm{min}} \right)^{3/2} \mathrm{m}.$$

This is the error in one coordinate—multiply by $\sqrt{3}$ for the error in 3D.

Much better performance is possible in principle. There are three main sources of accelerometer noise: thermo-mechanical (*i.e.* brownian motion of the proof mass), thermo-electrical (Johnson noise), and amplifier noise. Piezoelectric MEMs accelerometers tend to be dominated by the second of these, which scales as $1/f$ at low frequencies [19], so they are not well suited to inertial navigation. However, all accelerometers are subject to thermo-mechanical noise:

$$\sigma_a^2 = \frac{4k_\mathrm{B}T}{m\tau} = \frac{4k_\mathrm{B}T\omega_0}{mQ}, \tag{1}$$

where m is the proof mass, and τ is the damping time of its velocity; since the mass forms part of a small harmonic oscillator, $\tau = Q/\omega_0$ in terms of its natural frequency and quality factor. Plausible values for a MEMs device are $m = 10^{-3}\,\mathrm{g}$, $\omega_0/2\pi = 10\,\mathrm{kHz}$, and $Q = 10^4$, so that $\sigma_a \sim 30\mathrm{ng}/\sqrt{\mathrm{Hz}}$. Current devices are far above this limit, but the good news is that their sensitivity has improved exponentially with a slope comparable to Moore's Law (Figure 3). At the research level, 3-axis capacitative acclerometers (which have much better low-frequency behavior than piezoelectric ones) now exist with $\sigma_a \approx 1\mu\mathrm{g}/\sqrt{\mathrm{Hz}}$ in a $\sim 1\,\mathrm{cm}^3$ unit [22]. To our knowledge, these are not yet incorporated into commercially available IMUs, but they should be soon. The noise floor quoted above would enable meter-level positional accuracy over timescales of order an hour, which is probably longer than necessary to clear a building.

Gyro noise contributes to positional error since "strapdown" accelerometers integrate accelerations with respect to rotating body axes. There now exist research-grade MEMs ring gyros with noise floors $\sigma_g \sim 10^\circ\mathrm{hr}^{-1}\,\mathrm{Hz}^{-1/2}$ [22]. Without other constraints on orientation, this would yield positional errors $\Delta x(t) \sim a_\mathrm{rms}\sigma_g t^{5/2}$, where a_rms is the root-mean-square acceleration

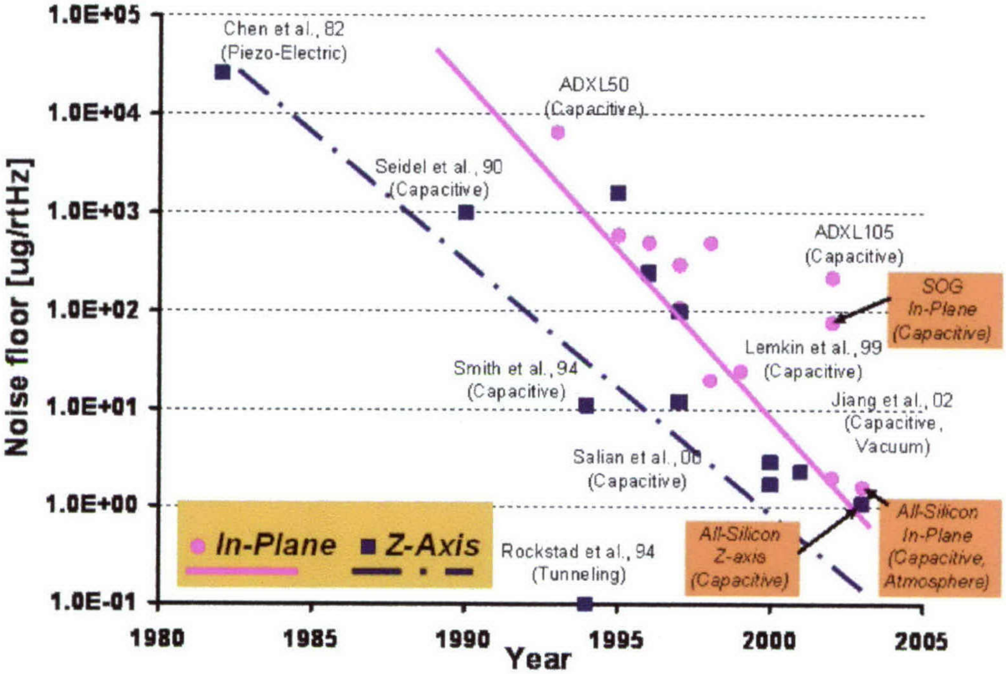

Figure 3: Noise floor for MEMs accelerometers (in $\mu\mathrm{g\,Hz}^{-1/2}$) versus time, from [22].

sensed by the accelerometers. The dominant acceleration is of course gravity, $a_{\rm rms} \approx 10\,\mathrm{m\,s}^{-2}$, so the positional error would exceed a meter after only one minute, even with perfect accelerometers.

In practice, IMU errors are often dominated by unknown DC offsets rather than noise. For example, an accelerometer bias of $1\,\mu$g contributes a 1.8 m error after 10 minutes. In principle, if sensor biases are constant, they can be calibrated against GPS measurements when available (probably using carrier phase, since only relative positions are needed). But the bias may vary with temperature or history, *e.g.* shocks or other insults.

Fortunately, there are several obvious strategies to correct for gyro drift. A small magnetic compass or magnetometer can be used to correct azimuthal orientation. Horizontal accelerations should average to zero over long timescales because vehicles and pedestrians have limited speeds, so the true vertical direction can be determined from long-term averages of the

vectorial acceleration. These strategies are commonly incorporated in commercial IMUs. It is probably possible to reduce drift further by modeling the walking (or running) process: this is the principle of the pedometer, which simply counts strides. A "smart" system could learn the stride length, *etc.*, of the individual soldier by calibrating IMU time series against GPS when available. It is particularly useful to recognize when the soldier is not moving and to stop integrating the velocity at those times. Except when using elevators, slidewalks, or vehicles, infantrymen do not exhibit unaccelerated motion with respect to the earth.

3.5 Visual Navigation

The characteristics of urban environments that make standard methods of geolocation difficult may, however, facilitate other methods. One such is *automated* navigation by landmarks. In other words, at least when the soldier is out on the street, systems can be imagined that would determine his position by imaging nearby structures and comparing with a precompiled database. For this to work well, the system should include the following elements.

First, the city (or that part of it where urban operations are to be conducted) should be mapped and geolocated three-dimensionally on a fine scale, ideally a meter or better. If it makes the job easier, the map should concentrate on prominent fixed structures having a rectilinear geometry, *i.e.,* buildings, while ignoring smaller, irregular, or changeable features. In densely built-up environments, these data are best acquired from high elevations. With multiple viewing angles, purely visual data might be adequate to the task, but radar—ideally interferometric SAR—might be a useful adjunct.

The second element would be a small digital camera or cameras mounted on the soldier, perhaps affixed to his helmet. These cameras could be quite small and light, as the required resolution is not stressing. The advent of digital cameras on cell phones has been enabled by, and has further encour-

aged, the development of small, low-power CMOS and CCD detectors. At the time of writing, megapixel CMOS sensors with good sensitivity, noise characteristics, and power levels ($\sim$ 100 mW at 15-30 frames per second) can be obtained. These can be used to create small ($\sim$ cm^3) cameras with a field of view and resolution comparable to the human eye($\sim 50°$, 1 mrad), and with better low-light performance.

The comparision of images with the mapping database requires substantial computation and storage. This might be done by electronics carried by the soldier, or by a remote facility. The former imposes a penalty in weight and energy stores on the soldier, while the latter costs bandwidth. Let us try to estimate these.

In the former case, the soldier must carry the complete 3D mapping database, at least for the urban area in which he operates. Let us generously assume that this is a volume 10 km on a side by 10 m high (many buildings will be taller, but their areal filling factor $\ll 1$), hence 10^9 m^3. At one-meter resolution, a wire-frame representation of all of this would require only a few gigabytes of storage; even this may be an overestimate, because the database may contain little if any detail about the interiors of buildings (in which case this method of navigation is useful only on the street, or at best near a window). Present-day nonvolatile RAM is already more than adequate to store these data; at the time of writing, 2 GB flash RAM cards can be had for a few hundred dollars and weigh less than an ounce. It is much harder to bound the computations required to compare the immediate scene with the database. We assume that machine-vision algorithms would be used to reduce the scene to a set of edges and vertices in projection; three-dimensional information might even be obtainable by comparing successive frames, if the soldier is moving. Matching this representation to the database is a problem in computational geometry. Fortunately a blind search is not required since a good initial guess of the soldier's position is likely to be available from past history or other inputs (*e.g.* inertial navigation, see §3.4). It is unclear to us whether the computations are beyond the reach of low-

power, portable processors. If they are, then it will be necessary to transmit the scene to a remote computation facility, which would then return the computed location in a few bytes. The bandwidth required for uplink is much less than would be required to transmit a raw image; even inexpensive digital cameras can compress their images by encoding into JPEG. Since only geometrical features need be represented for navigational purposes, much greater compression is possible. Let us assume a typical distance less than 100 m to nearby buildings; to represent edges at one-meter resolution over a typical field of view ($\sim$ 0.3 steradians) would then require only a few hundred bytes. Should it be necessary to transmit a few "frames" a second, the bandwidth required by such data is comparable to a voice channel.

Beyond these obvious questions of storage and bandwidth, there are subtler and perhaps more difficult software issues to address. Can the system we describe be made clever enough to ignore ephemeral features of the scene such as people and vehicles which, if not actually moving, are likely to have moved since the mapping database was constructed? What happens in tract housing or other neighborhoods where adjacent buildings are geometrically congruent? These issues deserve study.

In summary, we have described a high-tech version of the most ancient form of navigation: by visual landmarks. It is naturally complementary to GPS, because it will work best where buildings obscure much of the sky (but not all of it, if mapping must be done from above).

3.5.1 Visual relative navigation.

Even without the mapping database, image processing can be used to measure *changes* in position and orientation, yielding data similar to that produced by an IMU but perhaps with higher accuracy.

Consider the principle of the optical computer mouse. In these devices, a small (typically 16×16 pixels) sensor images the surface over which the mouse travels. Frame-to-frame comparison is used to estimate translations

$(\Delta x, \Delta y)$. No *a priori* knowledge of the surface is required. This application is rather forgiving of long-term drifts, as the user requires only to control motions of the cursor on his computer screen. He does not expect the cursor to return to its position of five minutes prior when the mouse does. Navigating in 3D by imaging objects at variable distances requires more data and computation than an optical mouse, but it can be done.

A major issue is to distinguish rotations from translations. For example, when a horizontally directed camera with a narrow field of view ($\ll 1$ steradian) images a stationary object, apparent motion of the scene could be caused either by the camera's transverse linear velocity with respect to the object, or by rotation around a vertical axis.

Rotations and translations are distinguishable over large fields of view. Suppose for argument's sake a 4π-steradian imager. (A close approximation might be achieved with two fisheye lenses). The scene can be thought of as projected onto the surface of a sphere centered at the camera. Pure translation causes features in the scene to flow along meridians of "longitude" that diverge from the point towards which the camera moves, called the "apex", and converge on its antipode.[4] Rotation causes a flow along small circles of "latitude" whose poles mark the axis of rotation. Scene motions are fundamentally angular velocities, so the scene motions caused by linear velocity are inversely proportional to the range of the object, whereas those caused by rotation are independent of range.

The general flow is a superposition of both kinds of motion, which can be distinguished. The key point is that rotation does not change the angular distance between any pair of features. Therefore, changes in angular distance or size can be used to diagnose the velocity of the camera and the ranges of objects in the scene. It is clear, however, that the visual data are unchanged if the camera's velocity and all ranges are rescaled by a common factor. So without further information, only ratios of ranges, rather

[4] The eighteenth-century astronomer William Herschel discovered the motion of the Sun relative to nearby stars by this method [16].

than absolute ranges, can be determined. The ambiguity can be removed by measuring the linear size, distance, or line-of-sight relative velocity of a single object in the scene. Possible methods include parallax (using two or more cameras of known separation and overlapping visual fields), laser or ultrasonic range-finding, or simply recognizing standard objects of known size (*e.g.* wall-outlet faceplate, beer can; but automated image recognition is not yet reliable, and such objects vary culturally). Alternatively, if an IMU or even a single accelerometer of known orientation with respect to the camera is available, then a lengthscale can be determined by comparing angular and linear accelerations. However range is found, it need be done only once in a given room, in principle.

How accurate might such a system be? We have described the method in terms of angular velocities, but one would want to track the angular positions of objects for as long as they are visible in order to minimize compounding of errors. Typical angular errors could then be no larger than the resolution of the camera, $\Delta\theta \sim 3\,\mathrm{mrad}$ if several steradians were imaged onto one or more megapixel sensors. The positional accuracy is then $\Delta x \sim \bar{R}\Delta\theta$ when the typical range to objects in the scene is $\bar{R}$; indoors, $\bar{R}$ is only a few meters. So $\Delta x \lesssim 1\,\mathrm{cm}$, much better than necessary, as long as a given set of objects remain in view and recognizable. However, when the camera passes from one room or corridor to another, the scene changes completely and quickly. Therefore, the system we have described would probably work best in conjuction with an IMU to bridge the gaps created by passage through doorways. IMU errors would go uncorrected by the imaging system only during these short time intervals and therefore would accumulate much more slowly than for a navigation system relying on an IMU alone.

Clearly, there is a good deal of potential in the combination of IMUs and machine vision, but equally clearly, this is not yet a mature technology and not a near-term prospect for the soldier.

4 BETTER MAPS

In this section we discuss issues of location and mapping as they apply to small units engaged in urban warfare. We were told by USMC briefers that soldiers in urban combat need 3D location, both of themselves and of their surroundings, to better than military standard GPS precision. Basically this is because, in the urban setting, an enemy position may be mere tens of meters from the soldier (as opposed to the hundreds of meters, or kilometers, typical of open terrain warfare) and also tens of meters or less from innocent civilians. It would obviously be very useful if soldiers could readily locate themselves, other members of their unit and individual features of their surroundings (for munitions placement) with, say, one meter accuracy.

Despite the digital and communications revolution, the paper map continues to be the mainstay of the grunt on the ground (or in the HMMWV). Certain things have changed: modern maps are based on overhead imagery and can locate fixed features with one meter accuracy, even with open-source data; the mapping data for large regions, hundreds of kilometers on a side, fit handily on a CD and special-purpose maps can be printed out on the fly in the field; because maps are derived from digital data, the field-level map database can be rapidly updated (perhaps by flying in a new CD). Certain things have not changed, however: for the infantryman, using a map is still a matter of looking at ink on paper and using his visual skills to match what he sees around him to abstract map symbols; despite the fact that maps are now derived from images, military maps provide almost no detailed information about buildings, giving only general descriptions like "residential", "commercial", "industrial", etc. Modern computation, communication, geolocation, and display technologies could enable major improvements on current methods of providing mapping information to the combat soldier, and our goal in this section is to point out some "low-hanging fruit" in this technology area. As elsewhere in this report, we try to be mindful of the principle that, if any

technology is to be useful to the foot soldier, it must be light, non-distracting, easy-to-use and manifestly more useful to his task of keeping alive and killing the enemy than an equivalent weight of ammunition. We also note that we have not been briefed on the full range of mapping technology work going on within the DoD and are aware that some of our suggestions may already be under development.

4.1 Urban Tactical Planner

During our briefings at the Jason summer study site, we were made aware of a particular mapping innovation called Urban Tactical Planner (UTP), a product of the Army's Topographical Engineering Center (TEC, Ft. Belvoir) [15]. Mr. Joe Harrison of TEC generously provided us with documentation on the UTP and, ultimately, a briefing at Ft. Belvoir. The UTP is more a mission planning and rehearsal tool than a combat map, but our attempt to understand the pluses and minuses of the UTP helped clarify our thoughts about the harder problem of constructing digital maps that would be useful in urban combat.

The UTP is basically a commercial GIS viewer coupled to 1) a city map database locating all the roads, rivers and waterways, and major infrastructure features and 2) complete overhead imagery of most of the mapped area. As many as a few hundred of the most important buildings visible in the imagery (such as police stations, hotels, army barracks, government buildings, etc.) are manually annotated as to function in yet another layer of the GIS. The software allows the user to "fly through" the city, observing the abstract road map, or the overhead imagery, as they would be seen through a camera carried on board the fly-through aircraft. Unfortunately, the original version of the UTP does not allow the user to see a ground-level view. This is related to the fact that only unprocessed, one-look overhead imagery is used, so that it would in any case be impossible to infer with any fidelity what a ground-level scene would look like. We are told that a later version of the

system, the Enhanced UTP (EUTP), at least partially corrects these defects: a wireframe model of the city is constructed from multiple overhead looks and the image is draped over the wireframe so that it can be viewed from any angle and altitude, thus allowing more direct rehearsal of an infantry action. However, it was not clear to us that this more advanced product was widely available, or likely to be so any time soon. Unfortunately also, an apparently useful feature to allow automated route-finding ("Battlespace Mapper") was removed from the current version of UTP.

A critical issue in the production of this system, or any system like it, is the degree of automation that can be brought to bear. According to J. Harrison of TEC, the UTP tool for any city can be produced by a group of a few people working for a few weeks (the UTPs for dozens of cities are in fact now available). It seems to us that this is only possible because what is added to the input data in the end amounts to the annotation at most a few hundred buildings about whose importance one has *a priori* information. In combat, one will need precise coordinates for many buildings whose importance could not have been known in advance. The only sound approach is to collect three-dimensional structural information (via multi-look imaging and/or laser ranging) on essentially all structures in the area of interest. The natural way to store this data would be as a wireframe with imagery to drape over the wireframe and use for extraction of information about building materials and the location of doors and windows. Since the areas of interest are relatively small (30 km by 30 km for a major metropolitan area), the collection of the physical data can be done rather quickly, especially if UAVs or conventional aircraft can be used for the collection. The hard part of the task is the automated extraction of the higher-level geometrical information from the raw physical imagery: if any significant level of human intervention is required, the problem becomes unmanageable. We suspect that that this sort of issue is well-studied in parts of the DoD that are not well-connected to TEC, but we did not have time to explore this issue during the summer study. If the requisite technology exists, it would be important to transfer it to TEC.

4.2 Display Issues

The paper map has the great advantages of robustness and low cost. The more sophisticated digital map, displayed on a laptop screen, is a plausible option for the command tent, but out of the question for use in combat.

The combat infantryman does, however, routinely wear night-vision goggles and it might be possible to include a heads-up map display in a similarly convenient package. If the mapping data were similar in nature to that of current military maps, a small flash memory would be more than adequate to store the data for a large city. We believe that the other hardware elements of the display could be made similarly light and low-power. If the map system could be integrated with geolocation and communication services of the type discussed elsewhere in this report, other useful features, such as automatically centering the map on the user's location, and marking the positions of other squad members, or other friendly units, would become possible.

Two aspects of the source data for modern maps which could be used to good effect, but are essentially edited out of the final product used by the soldier, are imagery and 3d information. Image databases are large and it is impractical to store all the image information for a whole city in the sort of low-impact display device envisioned in the previous paragraph. However, only a small fraction of the whole database would be needed on any given mission and the relevant data subset could be installed before the start of each mission (or, given adequate comms, downloaded as needed). This might make it possible to address the important problem of accurate targeting in the complex 3d environment of a city. If the soldier wants a distant fire support unit to put a round through a particular window in a particular building, he can put a cursor on the image in his heads-up display and read off the coordinates of the desired target (or, better yet, automatically send the coordinates to the appropriate recipient). The assumption, to be verified, is that the basic map imagery data can support the requisite absolute location accuracy (one meter is what we have in mind) of building features such as

windows. Since the mapping imagery is collected under at most a few view angles in order to infer 3d position, location error is likely to be a fairly non-uniform function of horizontal and vertical position. Nonetheless, it seems plausible that, by taking care, the image data needed to locate features to one-meter accuracy in a typical urban area can be collected. Perhaps the more difficult issue is the automated conversion of the image data to accurate feature location (absolutely essential if we are to annotate in this fashion a whole city). Note that this conversion must be applied not only to the original data from which the map is constructed, but also to the images gathered by the combat soldier who needs to geolocate a feature in the scene. If the processors carried by the soldier are not sufficiently powerful for automatic feature extraction, then as a stopgap, he might aid the system by identifying corresponding points in the mapped and current scenes.

Altogether, map display innovation is clearly a fertile field for invention and one which should be pursued vigorously to determine what is technologically possible and what is actually useful.

4.3 System Issues

There are some important issues concerning the conceptual model of how the map information is distributed to, and used by, the combat troops. It seems to us that it is important for the software to be set up so that the user can annotate his map database as he uses it. The point is that the military user will learn, via patrol and combat activity, more and more about the region/city for which he is responsible. This is by and large ephemeral information that has no need to go into the permanent database back in CONUS, but it can be of life-or-death importance to the soldiers during the days or weeks it remains useful and valid. The combat user needs a kind of digital "grease pencil" to incorporate this information for his own use. The current utilization concept does not appear to permit anything like this, which is a pity. Any such annotation facility should also have a

multi-level classification feature so that a unified database can contain all the information of interest to all customers in the company or batallion. There is a related issue of communicating information about database errors back to the map issuers in the US and making sure that they check user feedback and correct the master database as necessary.

4.4 A Note on Urban Maps

Maps of an existing urban landscape (e.g. from overhead views of it) give very limited descriptions of what is important to a force trying to secure a city. Even with up-to-date photography rooftops hide building interiors and obscure many entrances and passageways. If archives existed of urban area views taken while many of the buildings shown within them were still in early stages of construction a considerable part of this problem might be mitigated. Opportunities for collecting such archives will be considerable because of the great rate at which new areas are being urbanized and buildings in older urban areas replaced.

a.) Migration of population from the countryside into towns and cities is growing at a very high rate, especially in less economically developed countries.

b.) Because of the very high value of land in many urban centers buildings there are very often replaced long before the end of their useful lives.

Over the next two decades enough new building is expected in urban areas that, by the end of this period, an important fraction of existing urban structures will have been built during that interval. Continually archived overhead photography of selected cities could then give much of the desired ground level detail (and some interior structure description) associated with the very abundant new building. Diverting some national reconnaissance assets for the construction of such archives would probably not be an optimal use of those assets. However, the cost and benefits of continual purchase

and archiving of commercially available overhead photography of potentially interesting urban sites should be studied. The best resolution in commercially available digital imagery of earth surface sites is from the QuickBird satellite, which makes images at 0.6 m (cf. Table 2). Even with such sub-optimal resolution, archiving repeated observations of urban sites may have future value. The price of QuickBird images varies depending on many things, such as tasking priority and cloud coverage, but are in the ballpark of \$2000 for a minimum order of 64 km^2. The purchase of archival data from continued monitoring of 2×10^3 cities at 6 month intervals might then be about \$12 $\times 10^6$ yr^{-1}.

Table 2: Space and Aerial observation system parameters [14, 6]

Platform & Camera	Altitude	Pixels in line	Resolution
Satellite: QuickBird	450 km	16×10^3	0.6 m
Aerial: film	10 km	NA	0.25 m
Aerial: digital ADS 40	4 km	20×10^3	0.2 m

5 FINDING SNIPERS

Few things concern an infantryman in combat more than to know by whom, or at least from where, he is being shot at. One desires to improve upon the technique illustrated in Figure 4. We therefore examine several technical approaches to finding snipers.

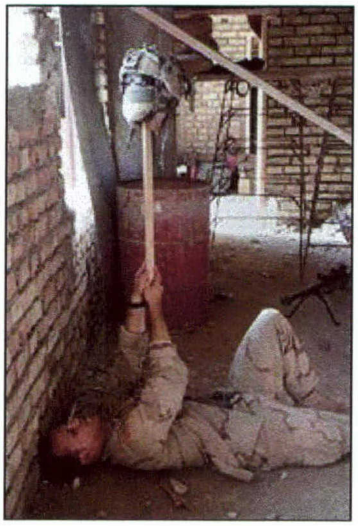

Figure 4: Baiting a sniper in Iraq. (Jim MacMillan, Associated Press, *New York Times* 8/22/04.)

5.1 Helmet-Mounted Passive Acoustics (A-Sniper)

Technology exists which should allow a small array of microphones to be attached to a soldier's helmet, along with a small microprocessor that is activated only when a supersonic shock wave from a sniper's bullet is detected. The array determines the direction of the sniper, and with a series of light-emitting diodes (LEDs) along the rim of the helmet, indicates the direction of the sniper without distracting the soldier. The system is a refinement of others previously developed such as PILARw and Boomerang, but unlike these, it is designed to be wearable.

5.1.1 Introduction

Soldiers frequently try to locate a sniper from the sound of the gunshot. In exercises we watched at the Matilda Village urban warfare training facility, we watched an anti-sniper exercise. A shot is heard, the platoon disperses seeking cover, and soldiers shout, "I think it came from *that* building!" In an urban environment, however, the sound often reverberates and echoes, and the sound can give a very misleading direction. Moreover, the sound of the shockwave from the bullet (and this is usually what the soldier hears first, since the bullet travels faster than sound) points back to the path of the bullet, not to sniper; the difference in angle can be 45 degrees or more, depending on the unknown Mach number.

To improve accuracy and to automate the process, an acoustic anti-sniper system called Boomerang was developed by BBN Technologies. Early versions of this system were rapidly deployed in Iraq over the past few months, intended primarily for use in static locations. An improved Boomerang system will be deployed soon.

As originally developed, Boomerang has three operating concepts. Its most straightforward version is in the form of an antenna array that can be mounted on the ground (near, for example, guard post) or on a vehicle. This is the system that was chosen for quick deployment in Iraq. A second and far more complex system uses helmet mounted microphones, with the signals from multiple helmets exchanged, along with GPS locations, and then analyzed by small computers to detect the direction of the sniper. A third approach was considered primarily for an emergency backup, and it used the microphones on just one soldier operating autonomously. The BBN counter-sniper systems are described in papers dating to the 1990s [7, 8]; more details and two patents are available online [3].

We will argue in this report that the single helmet sniper locator can be easily improved to the point that every soldier in danger could have one installed in his helmet. The system can be lightweight (two ounces), inexpen-

sive, accurate, and not interfere with the situational awareness of the soldier. The key aspects of this system are the following:

1. Six small microphones mounted flush with the surface of the helmet. A helmet cover or camouflage would not interfere with operation.

2. A small coil used to measure the instantaneous orientation of the helmet with respect to the Earth's local magnetic field.

3. An ultrasonic microphone that detects the shockwave of the bullet

4. A tiny flash-memory recording system that records high fidelity microphone output for about one second after the bullet shockwave is detected.

5. A microprocessor that cross-correlates the muzzle blast sounds picked up by the six microphones, determines their relative arrival time, and locates the sniper.

6. A light-emitting diode display on the bottom rim of the soldier's helmet that indicates (without distracting) the direction and elevation of the sound of the muzzle blast.

To be most useful, the anti sniper system must be so light that the soldier will decide that it is more valuable than a comparable weight of ammunition. It must not interfere with his mobility, nor can it distract him from his situational awareness. For those who have not been under fire, we find the following analogy useful. Imagine you are driving a car at 70 mph on a crowded freeway, with other cars tailgating and weaving in and out. Your situational awareness is key, and you can't even take the time to look down at a map without putting your life in danger. A system that guides without distracting is the only kind that a soldier will use.

5.1.2 The urban acoustic environment.

Sniper location in the desert is relatively easy; even the human ear is fairly accurate in locating the direction of a shot, although it can be confused by the bullet shock wave (which does not arrive from the direction of the sniper).

In contrast, in an urban environment, the acoustic signatures of sniper fire can be not only confusing but misleading. Echoes and reverberations can come from directions far removed from the true location of the sniper. This has lead many analysts to believe that accurate location of a sniper in the urban environment is hopeless. We don't agree. The key to the solution is the recognition that at least one soldier has a clear view of the sniper — the one that the sniper aimed at. For that soldier, the distant sound of the muzzle blast (ignoring subsequent echoes) is a good indicator of the sniper location.

Other soldiers, even if they are nearby, may not have a direct view of the sniper (he may be shooting down an alley), and they might not hear the direct muzzle blast, but only echoes.

The three bangs from a sniper's rifle

Modern military rifles shoot bullets at, typically, Mach 2.4. At that speed, the shock wave arrives from a direction of 65 degrees away from the direction of the sniper.[5] Unless the soldier is hit, the first sound he will hear is the crack of the shock wave from the passing bullet. The bullet slows, and after traveling several hundred meters, its speed can be reduced to half, say to Mach 1.2. Thus, the Mach number is a characteristic not only of the rifle and ordnance, but also of the range. At Mach 1.2, the direction of the shock wave differs from that of the sniper by 34 degrees – a 31-degree change from

[5] The shock makes an angle $A = \arcsin(1/M)$ with respect to the flight path,where M is the Mach number. The direction of arrival is 90 degrees different from this, $B = \arccos(1/M)$.

its original value of 65 degrees. Thus, the shock wave not only points away from the sniper, but by an amount that changes as it slows down.

The second bang heard is usually the sound of the bullet impact. If the bullet passes close by the soldier, but hits something 10 meters behind him, then this sound will follow the shock sound by about 1/30 of a second. Two sounds that close together in time can be distinguished by ear, and a simple microphone can measure that time difference with high accuracy. If the bullet ricochets, then there can be multiple pulses of impact sound.

The third bang is the muzzle blast from the rifle. If the sniper is at a range of several hundred meters, then this sound might arrive a second or two after the crack of the shock wave. If the soldier is the target of the sniper, then this sound will come from the direction of the sniper, perhaps followed by echoes from buildings.

For other soldiers, not in the line of sight of the sniper, the only sound they hear might be echoes of the rifle muzzle blast, or echoes of the shock wave. These sounds, coming from multiple irrelevant directions, can be confusing and misleading.

For completeness, we mention a sound that we have not used in our system: the sound of the turbulent wake of the bullet. If this could be detected and identified, it contains a great deal of information about the bullet path. However, we are not aware of experimental measurements of the intensity and potential usefulness of this sound.

Helmet orientation measurement

Jeff Mazurek of BBN Technologies told us that devices to measure helmet orientation have been developed, and that making that measurement is not a problem. For our purposes, what is needed is

1. A recording (snapshot) of the helmet orientation at the moment of the arrival of the muzzle blast sound, and

2. The orientation of the helmet at the time that the soldier is noticing the LEDs — so the helmet shows the location with respect to the current orientation of the helmet.

Overall direction is easily measured with a coil that detects the Earth's magnetic field, supplemented with a level.

How the helmet-mounted anti-sniper system works

The only part of the system that is in continuous operation (requiring power) is the supersonic bullet shockwave detector. This microphone has the sole purpose of detecting the high frequencies present in a bullet shockwave, and measuring their amplitude. The amplitude serves as a crude measure of how close the bullet came to the helmet.

The system will only trigger on the sound of a near miss, say within 10 meters. It does this by detecting the high frequency (above 20 kHz) component of the bullet shock wave. Because sounds at these frequencies are strongly absorbed by air, with an attenuation distance of only a few meters, the atmosphere is normally very quiet in this range, so there will be very low background.[6] The intensity of the shock wave falls off inversely with the distance from the bullet path, so a strong shock wave indicates a near miss.

If a squad is attacked but not hit, it is important that they know who was the closest to the bullet. That's what the high frequency shock detector can determine. Each solder can have a simple LED readout that indicates how close the bullet came, perhaps by its brightness.

It is valuable to determine if the bullet came close to any particular soldier, since that would be a person in the line-of-sight of the sniper. For that person, and maybe for only that person (if the sniper is well hidden), the first sound of the muzzle blast will come from the direction of the sniper.

[6] The high-frequency components of the shock fall off more slowly than those of ordinary sound waves because they are continually reinforced by nonlinear steepening of the shock front. For a typical supersonic bullet, the high-frequency cutoff $f_{\max} \approx 3R_{\mathrm{m}}^{-3/4}$ MHz, where R_{m} is the miss distance in meters.[12]

Echoes may follow from reflections off building, but the first bang from the muzzle will be from the direct path.

As soon as the high frequency pulse from the shock wave is detected, a small processor (ideally in the helmet) opens a short time window to listen for the muzzle blast. The time of arrival of the muzzle blast in three microphones is sufficient to determine the direction the sound is coming from. For the soldier who was targeted, this will be in the direction of the sniper.

From the time of arrival of the first rifle muzzle blast in each microphone, the processor can calculate the direction of the sniper. From the delay, it can get a rough estimate of the range. (Since the Mach number is not known, this may only be in a category of "probably close", "probably within 200 meters", or "distant.") The compass in the helmet records the orientation of the helmet at time the report bang is heard, so it can give the soldier a relative direction.

Note that the system does not have to measure the absolute time of arrival; rather, it needs to determine the relative time of arrival. The pulses in the three microphones may have a complex shape, but the relative arrival can be determined to high accuracy if the shapes of the three pulses are similar by a simple cross-correlation of the pulses.

A key technology limit is the cost of fast analog-to-digital (A/D) converters to feed the microprocessor. With a 30-microsecond accuracy, the location of the muzzle blast wavefront can be determined to an accuracy (at the helmet) of about 1 cm. With a 20 cm array size, the direction of the sniper can be determined to about 3 degrees.

A minor advantage of this system is that it doesn't depend on absolute direction; it is insensitive to local distortion in the Earth's magnetism (e.g. from nearby buildings) since it is using the same compass for sniper location and for pointing to him.

What if the muzzle blast is suppressed?

There are two reasons that silencers should not overly concern us. The first is that snipers don't like them. They often degrade the accuracy or the range of the sniper. We were told that silencers are currently not widely used by the enemy in Iraq.

The more important reason is that even silencers do not totally suppress the bang, particularly for the high power and large projectile used in sniper rifles. Although there are lots of distracting bangs in the urban environment (cars backfiring, wedding parties shooting off guns), there is likely to be only one bang detected in the two second following the shock wave of a sniper bullet – the bang of the muzzle blast. Thus the requirement that the shock wave be detected is critical; it suppresses most other noises that could be confused with the gunshot. Even a relatively quiet bang, one that might be missed by the ear, can be distinguished if the system is only sensitive for one second.

* * * * *

Our discussion of passive acoustics has emphasized a "single-helmet" system because of its technological simplicity. However, greater accuracy and robustness can be achieved by a multi-helmet system that uses the arrival times of the shock at several soldiers[8]: in particular, one can dispense with the muzzle report. In the past, a significant barrier to adoption of multi-helmet systems may have been the need for RF data links and relative geolocations among all participating soldiers, but these requirements would not be troublesome if they were already satisfied for other purposes, as we advocate in §§2&3.

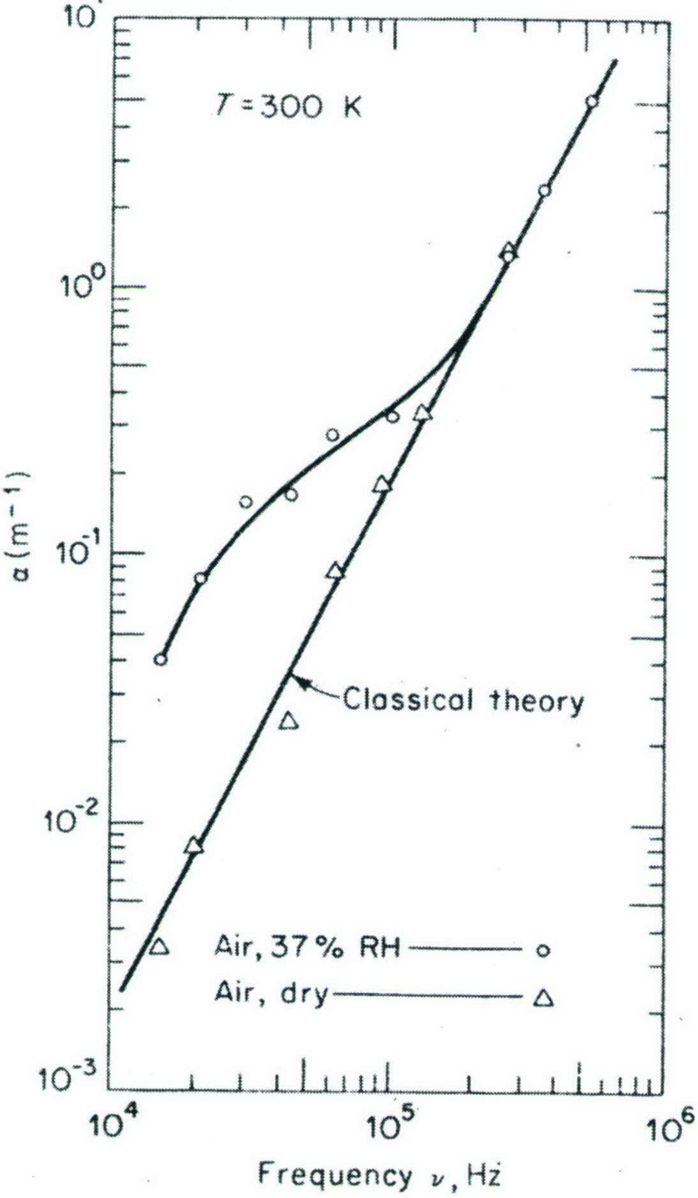

Figure 5: Atmospheric sound absorption. The coefficient α is the amplitude absorption coefficient; the absorption distance for power is $1/2\alpha$. Note that for moderate humidity (37% relative humidity) and 20 kHz, $\alpha = .08$, and the absorption length (for 63% absorption) is $1/2\alpha = 6$ meters. In 20 meters, such a signal is reduced to 4% of its original strength.

5.2 Optical Sniper Detection

Advances in photodetector and computer technology offer the possibility of optically detecting the muzzle flash of a sniper's rifle even in full daylight. We envisage a simple and self-contained system consisting of an electronic camera mounted on a small tripod connected to a controlling modified (including a frame-grabber) laptop computer by a few meters of cable.

We deliberately choose cheap COTS technology for a simple system with a single detector. No confirmation in other channels is required, as the rate of background events is low. The system alarms when a muzzle flash is detected, and gives the monitoring soldier the angular position of the flash displayed against an image of the scene. This does not locate the flash in three dimensions, but is sufficient for direct counterfire; by definition, a sniper engages in direct fire and so is vulnerable to direct counterfire from his target.

Such a system could have an effective range of at least 1 km, weigh less than 10 lb, cost less than $10,000 and be deployable at the squad level. It might be particularly useful in urban warfare, in which opportunities for concealment of snipers are plentiful, and sniper fire may come from high elevations. We envision the computer in a dugout, foxhole or other protected position, connected to a camera just outside. When a muzzle flash is detected the computer gives an audible indication and on its display (which continuously shows the image detected by the camera) encircles the pixel in which the flash was detected with a red circle or other indicator. The soldier can then take prompt and appropriate action.

The human eye is capable of detecting muzzle flashes. Unfortunately, it is not capable of staring for extended times, partly because of the limited human attention span and partly because soldiers are needed for other activities. Also, the eye does not instantaneously visualize a large solid angle. If it detects a flash, it is usually in peripheral vision, and is poorly located. This is not a difficulty when the flash is part of a continuous train of events

(a moving object, or a burst of fire from an automatic weapon) because the man can turn his attention to the source of the visual disturbance, but is an insuperable problem when the threat is a sniper who may fire one round a day.

The obvious difficulty with visible light sniper detection is daylight. Past systems have proposed other means (medium wave IR detectors, radar, acoustics, *etc.*) to avoid this difficulty, but run into other problems. For example, MWIR systems such as Viper suffer from the limited pixel count and higher noise of detectors of longer wavelength radiation. We propose to use the rapid rise of the visible muzzle flash to detect it in the presence of the daylight background. This permits us to take advantage of the cheapness, robustness and mature technology of visible and near-IR light detection. We need only a single sensor package at one point, rather than a network of distributed sensors whose data must be combined. Although we discuss the specific problem of sniper detection, a similar system on an aerial platform could be used to monitor a battlefield for mortar or artillery fire.

Consider a pixel of solid angle $d\Omega$ at range R. In daylight conditions the scattered sunlight received from such a pixel has intensity

$$I_{\text{scatt}} = I_{\text{Sun}} a(\vec{\Omega}_1, \vec{\Omega}_2) d\Omega,$$

where $a(\vec{\Omega}_1, \vec{\Omega}_2)$ is the bidirectional albedo and all quantities are implicitly integrated over frequency. We adopt $a(\vec{\Omega}_1, \vec{\Omega}_2) = 0.3/(2\pi\,\text{sterad})$. An optical system of aperture A will collect a power in scattered sunlight

$$P_{\text{scatt}} = I_{\text{Sun}} a A d\Omega.$$

Taking a quantum efficiency (including optical system throughput, *etc.*) $\epsilon = 0.5$, mean photon energy $h\nu = 4 \times 10^{-12}\,\text{erg}$ ($\lambda = 500\,\text{nm}$), and integration time $t = 4\,\text{ms}$ yields a background count

$$N_{\text{background}} = \frac{I_{\text{Sun}} a A d\Omega \epsilon t}{h\nu} = 5 \times 10^7$$

for an assumed $d\Omega = 2.5 \times 10^{-7}$ sterad (a 0.5 m $\times$ 0.5 m pixel at 1 km range, corresponding to a 25μ focal plane element at a focal length of 50 mm) and

$A = A_{\rm lens} = 6$ cm^2 (a 50 mm focal length $f/1.8$ lens). For a 1024×2048 pixel detector this corresponds to a (projected) 500 m $\times$ 1 km imaged swath, or about $28^\circ \times 57^\circ$, large enough to be useful.

Published quantitative data on muzzle flash are very scarce. The following results are fitted to experiments on guns of 1.575″–15″ caliber, and must be extrapolated to small arms and mortars[17]:

- Duration $= 5.7 \times 10^{-6}$ sec $\times$ caliber (in) $\times$ muzzle velocity (ft/sec)
- Integrated emissivity $= 1.4$ cp-sec $\times$ charge (lb) $\times$ caliber (in) $\times$ muzzle velocity (ft/sec)

For an AK-47 round with an assumed charge of 2 gm (30 grains), caliber 0.30″ and muzzle velocity 2400 ft/sec the integrated emissivity is 4.4 cp-sec and the duration is 4 msec. An 81 mm mortar with a 120 gm charge and muzzle velocity of 1000 ft/sec produces a flash of integrated intensity 1200 cp-sec and duration 18 msec. For light near the middle of the visible spectrum 1 cp = 19 mW, so the AK-47 muzzle flash emits $E_{flash} = 85$ mJ of light, and for the mortar $E_{\rm flash} = 22$ J. These estimates are, at best, approximate.

It is important to note that the brightest component of muzzle flash, called "secondary flash", is produced by the re-ignition of unburned propellant and combustion products in the air. This re-ignition can be suppressed by the addition of a variety of compounds (typically, but not exclusively, alkali metal salts such as K_2SO_4) to the propellant, with a consequent reduction in muzzle flash brightness by a factor ~ 100 and in duration by a factor ~ 3[17, Figs. 22.4&22.6]. Much propellant used on the battlefield contains flash suppressant. Quantitative data on the actual emission by weapons likely to be encountered is urgently needed.

The corresponding number of detected signal photons from the muzzle flash of an AK-47 (assuming no flash suppression) is

$$N_{\rm signal} = \frac{A_{\rm lens} E_{\rm flash} \epsilon}{4\pi R^2 h\nu} \approx 5 \times 10^6,$$

where we have taken $R = 1$ km.

At first this appears unfavorable, for $N_{\text{signal}}/N_{\text{background}} \approx 0.10$. However, the background is steady, while the flash signal rises in about 1 ms (the barrel length ≈ 1 m divided by the velocity ≈ 1 km/sec). Hence frame-to-frame subtraction drastically reduces the background. If its variations are only statistical then the ideal signal-to-noise ratio becomes

$$\left(\frac{S}{N}\right)_{\text{ideal}} = \frac{N_{\text{signal}}}{N_{\text{background}}^{1/2}} \approx 700.$$

This may be overly optimistic. For example, a CCD detector would require a combination of iris diaphragm (reducing A) and filter to reduce the background signal by a factor of 1000 to $\sim 50,000$ photoelectrons (about half the well capacity), which would reduce the S/N to ≈ 23. A photodiode detector does not have this limitation, but would require about a ten-fold reduction in background flux in full daylight to remain in the linear regime at a bias less than 10 V. This leads to $S/N \approx 200$, significantly below the ideal value but better than that achievable with a CCD. Still, muzzle flash detection in full daylight is permitted by photon statistics, even with system performance far below the ideal estimates. However, if the muzzle flash is suppressed by two orders of magnitude or more (by the use of non-flashing gunpowder) optical detection would be much more difficult.

It may be possible to increase S/N over the preceding estimates by as much as two orders of magnitude by the use of a red/near-IR filter and silicon (CCD or photodiode) detectors sensitive in the red and near-IR. Figure 7 shows that muzzle flash is much redder in color than is sunlight. Its infrared flux is much greater than would be inferred from the old emissivity data cited previously (almost certainly obtained with a photomultiplier or photographic emulsion insensitive to red and infrared light, although this is not stated). In addition, use of a red or near-IR filter would exclude most of the solar background (only 12% of solar photons have wavelengths in the range 800 – 1000 nm) without greatly attenuating the muzzle flash signal.

According to [17], the data of our Figure 1 are not quantitative be-

cause of uncertainties in detector sensitivity. Quantitative estimates of the improvement to be obtained by use of a red or near-IR filter and near-IR sensitive detectors will require new quantitative data. In particular, the detectability of muzzle flash when flash-suppressing powder is used remains uncertain.

There is probably little background of optical transients rising as fast as muzzle flashes in natural scenes. Sun glints from stationary objects rise in approximately $t_{\text{glint}} = \theta_{\text{Sun}}/\dot{\theta} = 120\,\text{s}$, where $\dot{\theta}$ is the angular rate of the Earth's rotation and θ_{Sun} the angular size of the Sun. However, glints from moving or rotating objects (automobiles, water waves) are much more rapid. A modest measurement program may be required to quantify the rate of rapid background transients in realistic conditions.

5.2.1 Categories of detection schemes.

The fundamental problem in detecting muzzle flash is that a brief transient must be searched for in each of a large number of pixels. A brute-force approach would require frame-to-frame differencing and comparison to a threshold of N_{pixel} (typically 2×10^6) pixels every 4 ms. Reading out data from the sensor at this rate is challenging (though perhaps not beyond the state of the art: see below). We therefore consider several schemes to circumvent this difficulty.

1. Non-imaging single-pixel detectors that are illuminated by the entire solid angle, Ω of interest. Detection by such a detector could trigger the recording of a single image from a spatially resolved detector array of N_{pixel} elements. The incident flux would be divided between these single pixel and array detectors with a beam splitter (a more sophisticated variant would use an electro-optic switch triggered by the single-pixel detector, but this is unnecessary because the signal is strong and the factor of two lost in a beam splitter is not crucial). Single pixel detectors with good near-IR response (Si photo-diodes, for example) are

available, but $N_{\text{background}}$ exceeds that in a N_{pixel} array covering the same field of view by a factor N_{pixel}. The single pixel detector therefore has an ideal S/N smaller than that of the N_{pixel} array by a factor $N_{pixel}^{-1/2}$, generally < 0.001. This is prohibitive, even given optimistic assumptions as to the brightness of muzzle flashes, and even without considering the fact that the increased background flux would require an additional iris contraction or attenuation factor of N_{pixel}^{-1} (and yet another reduction in achievable S/N of $N_{\text{pixel}}^{-1/2}$).

2. One-dimensional detection schemes collapse a two-dimensional array of N_{pixel} elements into flux histograms along two orthogonal axes. A muzzle flash appears as a simultaneous transient of the appropriate duration and temporal shape in each histogram. The locations of these transients can be used to locate the flash. S/N is greater than that of a single-pixel detector by a factor $\mathcal{O}(N_{\text{pixel}}^{1/4})$, but less than $(S/N)_{\text{ideal}}$ by the same factor, where N_{pixel} is the number of pixels in the two-dimensional array. Typically $N_{\text{pixel}} \sim 2 \times 10^6$ so that $N_{\text{pixel}}^{1/4} \sim 38$, a significant factor.

3. Two-dimensional detectors: It is possible to subdivide a field of view into a smaller number $N_{super} \ll N_{\text{pixel}}$ of super-pixels, with a beam splitter dividing the light between the full resolution and the super-pixel arrays. N_{super} is chosen so that the problem of reading out, differencing, and comparing to threshold the data from this coarse array is manageable. When a signal is detected in the coarse array the fine array, kept in its reset state, it triggered to collect an image. S/N is less than the ideal value by a factor $(N_{\text{super}}/N_{\text{pixel}})^{1/2}$, but greater than that of a single pixel detector by the factor $N_{\text{super}}^{1/2}$. For $N_{\text{super}} = N_{\text{pixel}}^{1/2}$ S/N assumes the same value as for the one-dimensional scheme, which resembles a super-pixel array with one-dimensional super-pixels.

A Notional One-Dimensional Muzzle Flash Detector

Consider the notional one-dimensional muzzle flash detector illustrated in Figure 6. A lens of focal length $f \sim 10$ cm produces a converging beam that passes through a wavelength-selective beamsplitter. We denote the two beams as "red" and "blue" even though both would probably be in the red/near-IR part of the spectrum. The purpose of the wavelength separation is to add another criterion by which muzzle flash may be discriminated from any background transients.

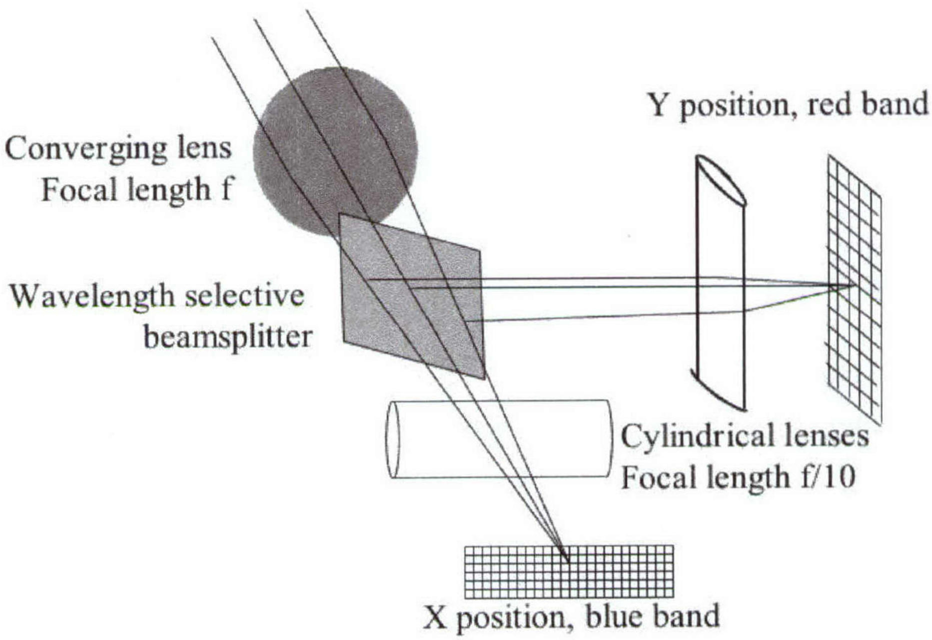

Figure 6: A passive optical muzzle-flash detection scheme. The scene is divided into two wavelength ranges and compressed in two orthogonal directions, each imaged on a rectangular CCD detector read out at high rate. See text for details.

The two emerging beams then pass through two perpendicular cylindrical lenses. These lenses (focal length $f_2 \sim 2$ cm) produce an asymmetrical im-

age compression of 5:1 and focus onto rectangular CCD detectors. We imagine a focal plane (without the cylindrical lens) spanning 1000×1000 $15\,\mu$m pixels. The system's field of view at 1 km would be about $500\,\mathrm{m} \times 500\,\mathrm{m}$. Wider fields could be monitored with multiple systems or straightforward modifications. The spatial resolution would be about 0.5 m in each direction.

The two CCDs are read out in an unconventional fashion. Each cylindrical lens restricts the illumination on the focal plane to 1000×200 pixels. The 200 rows are transferred into the serial register every 3 msec. It takes about 10 μsec to shift each row, for a total of 2 msec to transfer all the charge into the serial register. During the 1 msec interval between row dumps, the serial register is read out at a leisurely 2 Mpix/sec. This readout mode essentially collapses the scene in one dimension, producing a one-dimensional vector of intensity.

The two detectors are oriented to produce intensity plots in two orthogonal coordinates. A transient excess of counts in each plot identifies a single pixel in the two dimensional image which is the origin of the muzzle flash, without the need to process any two dimensional data arrays. The price of this "miracle" is a reduction in S/N because of the increase in $N_{\mathrm{background}}$ in each row sum. Note that because this increase only occurs in the row sums (rather than the individual pixels) detector limits may not require a corresponding increase in filter attenuation or reduction in A.

A candidate muzzle flash would need to satisfy the following criteria:

1. Joint $> 5\sigma$ detection in both channels,
2. Ratio of "red" to "blue" fluxes consistent with muzzle flash spectrum,
3. Temporal shape of flash consistent with expectations.

In this section we present a notional super-pixel muzzle flash detector, as illustrated in Figure 7. A beamsplitter divides the incident beam into subbeams of roughly equal intensity. One subbeam goes to a CMOS focal plane array, perhaps of 2048×2048 pixels, which sits in its reset state, ready to take a single image when triggered. This image would localize a muzzle flash to a single pixel, perhaps 0.5 m $\times$ 0.5 m at 1 km range. the other subbeam goes to a coarser (perhaps 16×16) photodiode array (available as COTS from Hamamatsu). In this example $N_{\text{super}} = 16^2 = 256$ while $N_{\text{pixel}} = 2048^2 = 4,194,304$, so S/N for flash detection in the coarse array is less than the ideal value by a factor of $16/2048 = 128$. As photodiode technology advances it would be possible to use photodiode arrays with more elements to increase N_{super} and to offer higher S/N.

Each of the 256 superpixels would be read out and time-differenced every msec. Detection of a flash would send a trigger signal (within a msec, while the flash is still bright) to the high resolution CMOS array. Once triggered the array takes a 2 msec exposure and the result is stored. After it has been read out and reset (perhaps after a tenth of a second) it takes another image (if the read out and reset times exceed half a second it would be desirable to have another CMOS array to take the second image after a shorter interval, with an additional beam splitter dividing the light between the two high resolution arrays). The flash would have decayed between the two high resolution images, so differencing them would produce a high resolution (0.5 m in our example) image of the flash, located on the background scene.

*****

It may be possible to dispense with the coarse photodiode array. CMOS imagers have advanced rapidly, so that one can now find megapixel sensors that offer several hundred frames per second at full resolution: for example, the Mikrotron MC1310 (1280×1024 10-bit pixels at 500 fps, power $\lesssim 6$ W);

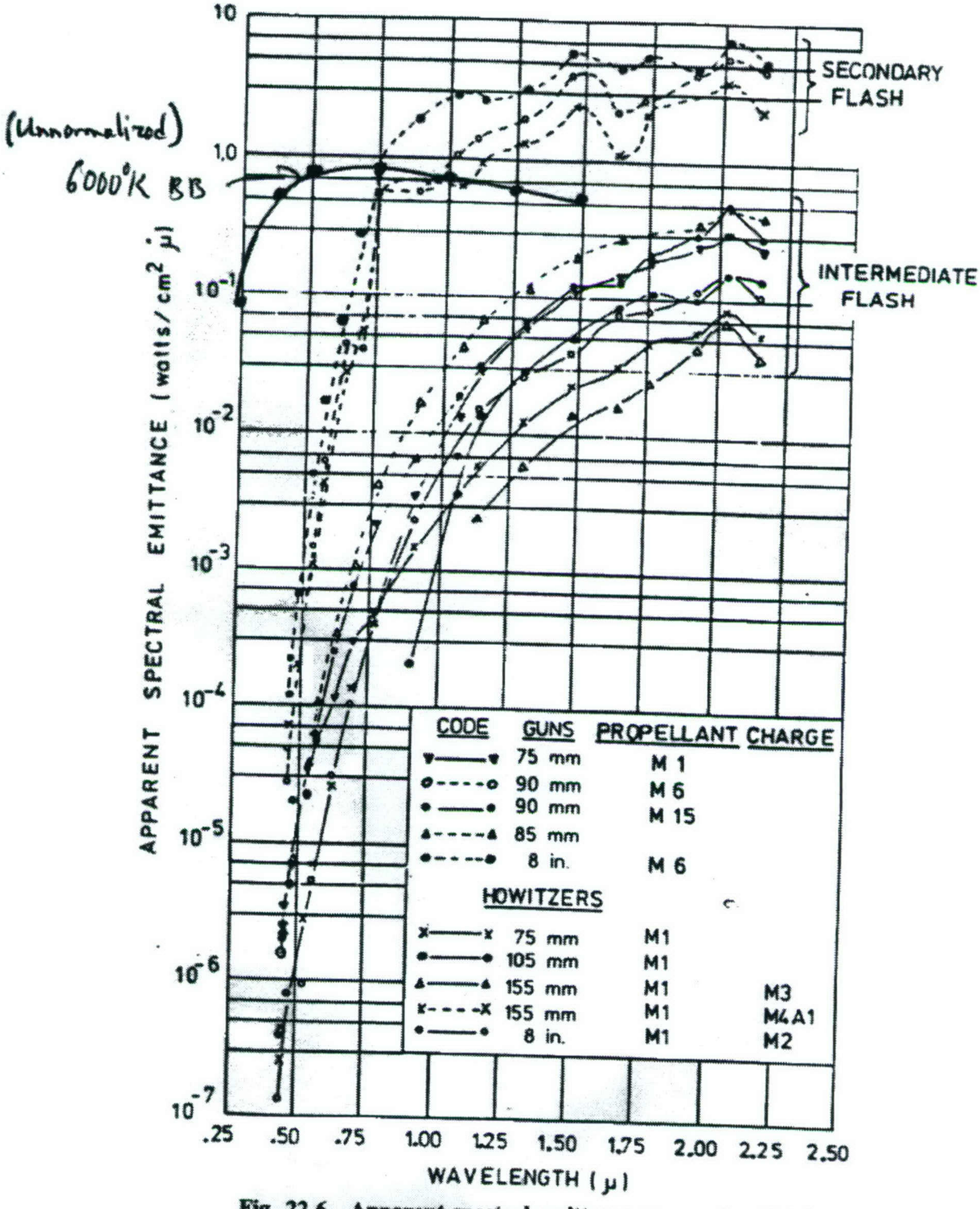

Fig. 22.6 Apparent spectral emittance vs wavelength λ⁶.

Figure 7: Spectrum of muzzle flash. (Reproduction of Fig. 22.6 of [17], which is based on [4].)

or the Fast Vision FastCamera13 (similar specs). The former at least, for which we were able to obtain more details [21], allows summing of pixels in 2×2 blocks to reduce the data rate without losing sensitivity. The quantum efficiency of these devices is not as good as that of CCDs because some of the pixel area is blocked by the associated electronics, but it is quite respectable: *e.g.* 25% at 500 nm & 5% at 900 nm for the MC1310; and based on the spectral response of other (slower) CMOS sensors, this could probably be substantially increased in the red if the manufacturers were motivated to do so. The readout noise of CMOS sensors is also higher than that of CCDs but probably acceptable at the light levels contemplated here. The great advantages of CMOS sensors over CCDs are their much lower power consumption and the direct readout of each pixel. With appropriate design, the latter feature might allow differencing of successive time samples directly by the circuitry on individual pixels.

In summary, the characteristics of recent high-speed CMOS sensors appear to be well suited to the detection of optical flashes, and are likely to be even more so in the near future.

Next Steps

Any serious attempt at muzzle flash detection will require a better characterization of both the signal and backgrounds. This will allow a quantitative comparison of candidate detection schemes, and rapid prototyping. We estimate that, should it prove viable, the one-dimensional scheme described above could be implemented in a crash program in under 3 months. The hierarchal super-pixel two-dimensional system, or perhaps (if workable) the standalone CMOS sensor, require only COTS components and a prototype could be built even faster.

5.3 Active Sonar

Sonar would seem an odd choice to track a supersonic object. However, no bullet-tracking system is likely to help the soldier avoid the *first* shot. Instead, the goal is to reconstruct the bullet trajectory. For this purpose, sonar has the advantage that the range-Doppler ambiguity involves the speed of sound (c_s) rather than the speed of light:

$$\Delta R \Delta V \approx \lambda c_s/2. \tag{2}$$

By this measure, sonar is a million times more precise for a given wavelength λ. This is not really a fair comparison, however, since even without range resolution, CW radar can reconstruct the trajectory by tracking bearing and Doppler. A reasonable wavelength is $\lambda \sim 1\,\mathrm{cm}$ since this is approximately the size of the bullet, which translates to $f \sim 30\,\mathrm{GHz}$ for radar and $f \sim 30\,\mathrm{kHz}$ for sonar.

Sonar suffers from attenuation. The kinematic viscosity of air under standard conditions is $0.14\,\mathrm{cm}^2\,\mathrm{s}^{-1}$, so that the damping length of the amplitude is

$$\ell = \frac{c_s^3}{(2\pi f)^2 \nu} \approx 60 \left(\frac{\lambda}{\mathrm{cm}}\right)^2 \mathrm{m}, \tag{3}$$

in dry air, and roughly ten times less at reasonable humidities (Fig. 5), which is still acceptable for a system that is designed to track at ranges less than 10 m.

The Doppler shifts produced by a supersonic object are surprising, so we derive them from scratch. Let us choose the origin of time so that the position of the bullet along its trajectory at time t' is Vt', and closest approach approach $R = R_{\min}$ occurs at $t' = 0$. The bullet's velocity V is assumed constant over the time intervals of interest, and changes in sound speed due to the shock are neglible except very near the bullet. A wave reflected from the bullet at time t' will be received by the sonar (assumed stationary in the air) at $t_{\mathrm{rec}} = t' + (R/c_s)$ and was emitted at $t_{\mathrm{em}} = t' - (R/c_s)$, where R is the

distance d_{BS} in Figure 8,

$$R = \left[R_{\min}^2 + (Vt')^2\right]^{1/2} \;\; = \; R_{\min}\csc\theta\,,$$

and θ is the angle between the bullet trajectory and the direction of arrival of a sonar echo as indicated. in Fig. 8. One can also see that $t_{\rm rec} = d_{BS}/c_{\rm s} - d_{BO}/V$, whence

$$t_{\rm rec} = \frac{R_{\min}}{V}\left(\frac{M+\cos\theta}{\sin\theta}\right). \tag{4}$$

We have introduced the Mach number

$$M \equiv \frac{V}{c_{\rm s}} \; = \csc\varphi.$$

From (4), it is evident that $t_{\rm rec} > 0$ if $M > 1$, *i.e.* the echo from a supersonic bullet is heard only after its closest approach. More interestingly, $t_{\rm rec}$ has a minimum value

$$t_{\rm rec,min} = \frac{R_{\min}}{V}\sqrt{M^2-1}\,,$$

(achieved for $\cos\theta = -M^{-1}$), which is the time at which the shock is heard, and thereafter there are *two* values of θ for each $t_{\rm rec}$, meaning that two echos are heard simultaneously from different points B, B' along the trajectory.

Since

$$\frac{dR}{dt'} = V\cos\theta = \frac{V^2t'}{R}\,,$$

it follows that

$$\begin{aligned}
\frac{dt_{\rm rec}}{dt'} \; &= \; \frac{d}{dt'}\left(t' + \frac{R}{c_{\rm s}}\right) \; = \; 1 + M\cos\theta, \\
\frac{dt_{\rm em}}{dt'} \; &= \; \frac{d}{dt'}\left(t' - \frac{R}{c_{\rm s}}\right) \; = \; 1 - M\cos\theta.
\end{aligned} \tag{5}$$

Considering the phase φ of the wave, the emitted and received frequencies must be related by $\omega_{\rm rec}dt_{\rm rec} = d\varphi = \omega_{\rm em}dt_{\rm em}$. Eliminating dt' between the relations (5) then yields the Doppler factor:

$$\mathcal{D} \equiv \frac{\omega_{\rm rec}}{\omega_{\rm em}} = \frac{1-M\cos\theta}{1+M\cos\theta}\,. \tag{6}$$

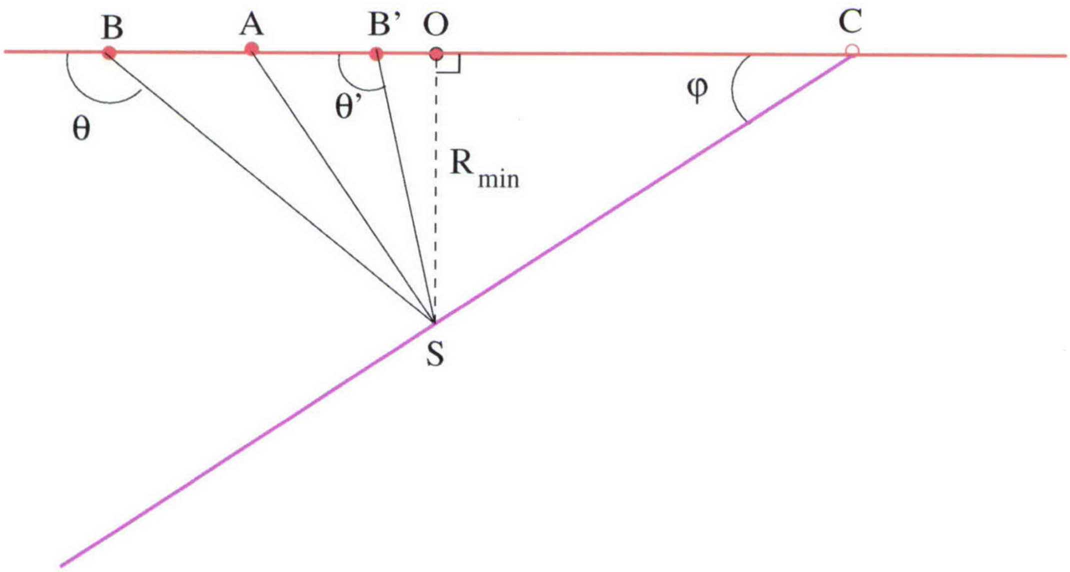

Figure 8: Active sonar geometry for $M \approx 1.8$. Bullet path $= \overline{BAB'C}$, sonar at S. First echo to be heard is reflected from A and is heard when bullet reaches C. $\overline{CS}$ is Mach cone, $\varphi = \sin^{-1}(1/M)$, and $\angle ASC = 90°$. Echoes reflected from B and B' arrive simultaneously at S but later than echo from A.

The Doppler factor $\mathcal{D}$ is negative when $|\cos\theta| > M^{-1}$, in other words when $R/R_{\rm min} > M/\sqrt{M^2-1}$, reflecting the fact that pulses are received in the opposite order from which they were emitted: $dt_{\rm rec}/dt_{\rm em} < 0$. Assuming the sonar transmits continuously, the first echo is heard simultaneously with the shock and arrives along $\overline{AS}$ with an infinite Doppler factor. At later times, the two simultaneous echoes from B and B' arrive with different Doppler factors $\mathcal{D}(\theta)$ and $\mathcal{D}(\theta')$ as given by eq. (6).

Thus if there are enough microphones on the soldier's helmet to resolve angle of arrival (a minimum of three is required), then the projection of the bullet trajectory onto the field of view is obtained by tracking bearing with time. The range resolution of the sonar allows each point on the trajectory to be located in 3D: for a 10 kHz bandwidth, a range cell is about 1.5 cm. As in the radar case, even for a CW system that has no range resolution, the 3D trajectory can be determined indirectly from the time dependence of the Doppler factor using (4) & (6):

$$\frac{d\mathcal{D}}{dt} = -\frac{c_{\rm s}}{R_{\rm min}}\frac{2M^2\sin^3\theta}{(1+M\cos\theta)^3}\,, \tag{7}$$

which gives $R_{\rm min}$. Note M can be determined from (6) by extrapolation to late times. Alternatively, one can use (6) to relate the Doppler factors of two simultaneous echoes to M, θ, and θ', and obtain a third relation among these quantities from (4):

$$M\csc\theta + \cot\theta = M\csc\theta' + \cot\theta'.$$

Apart from attenuation, the acoustic and radar powers required are comparable if thermal noise dominates in both cases. The "radar equation" states that the signal-to-noise ratio per pulse is the energy received divided by $k_{\rm B}T$. The (compressed) pulse length or integration time is set by the speed of the bullet, *e.g.* $\tau \approx 1\ {\rm ms}^{-1}$ if we want the bullet to move no more than $\sim 1\,{\rm m}$ during the integration time τ.

$$\frac{S}{N} \approx 15\left(\frac{P_{\rm trans}}{10\,{\rm mW}}\right)\left(\frac{\sigma_{\rm target}\sigma_{\rm antenna}}{1\,{\rm cm}^4}\right)\left(\frac{10\,{\rm m}}{R}\right)^4\left(\frac{\tau_{\rm int}}{1\ {\rm ms}^{-1}}\right)G, \tag{8}$$

where G is the gain of the receive array, assuming that the transmit array is isotropic. We have scaled both the target cross section and array area to $1\,\mathrm{cm}^2$ in the formula above. Note $10\,\mathrm{mW}$ acoustic power corresponds to 89 dB, comparable to a food blender. But at $30 \pm 5\,\mathrm{kHz}$, the sonar would be beyond the range of human hearing.

An important consideration when choosing between the radar and sonar solutions is the efficiency of transducers, that is, the ratio of transmitted electromagnetic or acoustic power to total electrical power consumed. The comparison is likely to favor radar. Also, while the radar can sense the bullet while it is still approaching, allowing it to switch from a low standby power level to a higher tracking level, the sonar power level cannot be adaptive since the bullet has already passed when the first echoes arrive, and subsequent emissions would not overtake it. For both of these reasons, the total electrical power requirements of a sonar system are likely to be much higher than those of a radar system with a similar detection range. This is a fundamental limitation of *active*-acoustic systems and should be borne in mind when evaluating any proposal in this area.

5.3.1 Helmet-mounted bullet-tracking radar.

The objective here is to develop, investigate and evaluate several design approaches to a bullet tracking radar that would provide an estimated location for the origin of sniper fire directed near a soldier with this radar. The instrument would be deployed on a single person and the readout would be an estimated location marked on an image (visible or infrared) of the scene confronting the soldier. The instrument would consist of a helmet-mounted antenna and an electronics package and battery the size of a cell phone.

We summarize the requirements as follows:

1. Track bullets that are near the soldier.

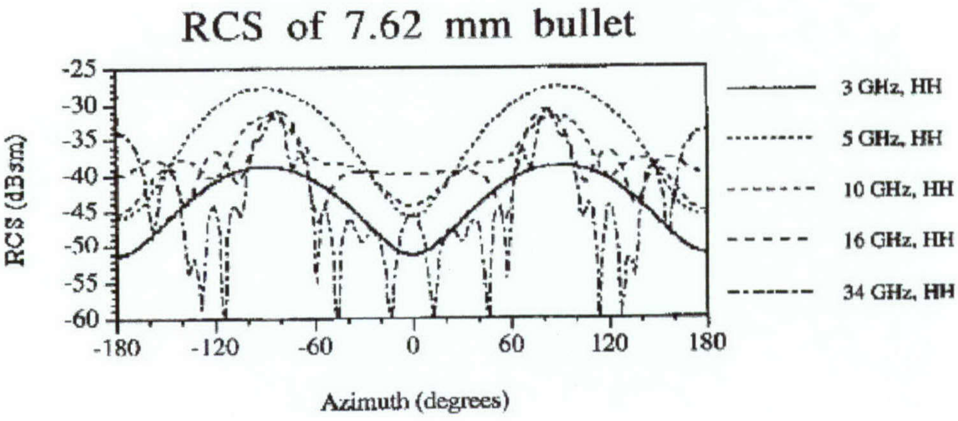

Figure 9: Radar cross-sections of a 7.62 mm bullet estimated by [2] are shown for several radar frequencies. Measurements by instrumentation radar are in agreement for X-band average cross section.

2. Point out the origin of sniper fire on an image of the scene confronting the soldier.

3. Do not add significantly to the volume or weight carried by the soldier or otherwise hamper combat effectiveness.

The radar that we envisage would track bullets a few tens to perhaps a hundred meters from the soldier. The bullets could come from greater distances, but would only be tracked near their closest approach to the soldier. The bullet trajectory and direction of origin would be deduced from a limited amount of radar data. Although bullets travel near a kilometer per second, very useful information on the bullet trajectory can be gathered in the time it takes for the bullet to travel 1 m. This information comes from the range, Doppler shift and angular location data supplied by the radar. Several radar design options emphasize one or more of these three types of radar data.

Radar design options: Radar frequencies vary over at least four orders of magnitude. For a given sized antenna the angular resolution typically improves as frequency increases. As shown in Figure 9, the maximum radar cross section is at $\sim$ 5 GHz for a broadside look and $\sim$ 35 GHz for an end-

on look. Since the bullet will generally be observed nearer nose-on at the longer ranges, the higher frequencies make more sense from a signal to noise point of view. Further, the higher frequencies provide more spatial resolution for a small, helmet sized, antenna. Hence, we have focused on the higher frequencies in our considerations.

Measurement concepts: We have considered four options in bullet tracking as shown in Table 5.3.1 below. Each of these has advantages and disadvantages as summarized in Table 5.3.1 and discussed below. All these options acquire Doppler (or equivalently signal phase) information and in some options range as well. For all the options some direction of arrival information about the radar echo is needed from the antenna. This ranges from simple monopulse-type direction finding from a few antenna elements to a complete phased array antenna that tracks the direction of the bullet. We discuss the different tracking options and the helmet antenna options below.

Table 3: Bullet Tracking Approaches

Method	**Advantages**	**Disadvantages**
Continuous Wave (CW)	Simplicity, good radial speed information Rejects low-speed clutter	No range information. Track ambiguities need to be resolved by multiple antennas
Frequency Modulated CW (FM-CW)	Range and speed information	Track ambiguities need to be resolved by multiple antennas
Pulse-Doppler	Range and speed information	System complexity. Track ambiguities need to be resolved by multiple antennas
Inverse SAR	Uses entire signal history	Track ambiguities need to be resolved by multiple antennas

Signal to noise considerations: Consider a simple CW radar with transmit power P_t, transmit antenna gain G_t, target cross section σ, receive a antenna area A_e, system losses of all types L_s, system noise temperature $T_{\rm sys}$, and receiver bandwidth B seeking a target at range r. The signal to noise ratio over a single integration time $\tau = 1/B = 2.5$ microseconds is

$$(S/N)_\tau \approx P_t G_t \sigma A_e Ls/[(4\pi r^2)^2 k\, T_{sys} B]. \qquad (9)$$

As an example, we consider the following case for 35 GHz radar

- $P_t \approx 100$ mW
- $G_t \approx 2$ (isotropic over the top hemisphere)
- $\sigma \approx 3 \times 10^{-4}\text{m}^2$ (end-on 35 GHz from Figure 9)
- $B \approx 400$ kHz (bandwidth needed to cover bullet Doppler shift)
- $A_e \approx 10^{-2}\text{m}^2$ (one of 12 patch antennas for receive)
- $L_s \approx 0.5$ or 3 dB
- $k = 1.38 \times 10^{-23}$ J/K
- $T_{\text{sys}} = 500$ K $(= T_{\text{ambient}} + T_{\text{electronic}})$.

With these parameters and a required S/N of 15 dB the maximum range is ≈ 13 m. So the concept of a bullet tracking radar appears within reach from a signal to noise point of view. Use of a sensibly longer coherent integration time, say $\tau = 1$ millisecond, raises the range to about 60 m. The longer integration time is quite practical since the bullet travels less than 1 m in 1 millisecond. $\tau = 1$ ms means we can divide the received signal in our 400 kHz bandwidth into bins or 'speedgates' of width $b = 1/\tau \approx 1$ kHz or a radial velocity bin that is 4.3 m/s. Most of the clutter, though large in cross-section (ground, buildings, even moving vehicles), will be confined to a few low-speed bins well separated from those containing the target.

Helmet antenna options: One can envision helmet antenna concepts that are as simple as one or two omni directional antennas or as complex as a full-up, completely filled phased array. Typically, one needs some direction of arrival information about the radar echoes in order to estimate an unambiguous track for the bullet. Here we describe two options: a simple approach with sufficient functionality to be useful, and a more powerful phased-array antenna.

A simple approach is shown in Figure 10. The helmet crown is used as a transmit antenna with a hemispherical coverage pattern. The lower part of the helmet is used to accommodate two tiers of 6 patch antennas each around

the helmet. This is the antenna that was used in the radar calculations for S/N above.

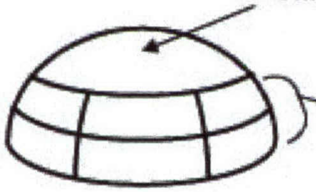

Figure 10: Simple helmet antenna. The transmitting antenna is in the crown and the array of receiving antennas stretches around the lower part of the helmet.

A fully functional phased array antenna for the receiver would enhance radar system performance significantly. First, a larger receiving antenna area will allow detection of the bullet at a larger range. In addition the phased array antenna would be able to provide direction of arrival information for radar echoes and thus an angular track for the bullet. However, a phased array tracking antenna would involve significantly more electronics, higher power consumption, and slightly more weight and volume for the soldier to carry.

The phased array antenna approach is illustrated in Figure 11. A tier of patch antenna elements spaced at approximately half the radar wavelength, or about 5 mm for 35 GHz radar, would extend around the helmet. Each element or small group of elements would need to have receive electronics associated with it. The number of elements would be in the thousands for a fully populated phased array; a thinned array is a possible option. In return for this complexity the bullet could be tracked more precisely and at greater range due to the beam forming capability of the antenna and the greater effective antenna area.

Standby and alert modes: To conserve power we suggest that the radar operate in two modes, search and alert. The search mode would use lower power but longer integration time. Once a bullet was detected, the

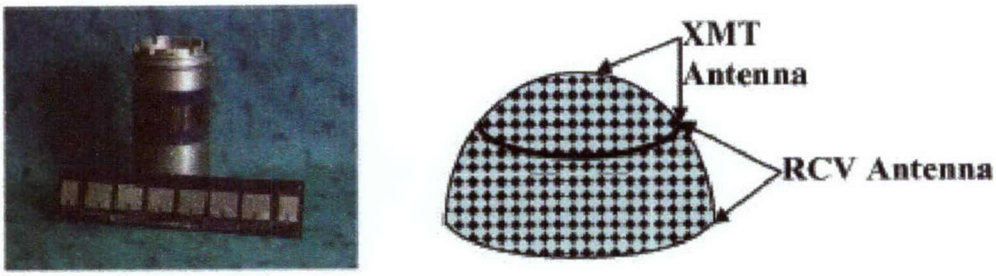

Figure 11: Fully functional phased array antenna on a helmet. The omni-directional transmitting antenna is in the crown of the helmet and the phased array elements are deployed in the band below the crown. At left we show an example of wrap-around patch antenna on the curved surface of a small ($\sim$ 6 inch diameter) missile (After [27]).

radar power level would increase, yielding a higher signal to noise ratio and hence better estimates of the trajectory. Turn-on times of mm-wave transmitters can be quite fast, a few hundred microseconds or less.

Below we discuss the four approaches of Table 5.3.1. The first three options involve use of different radar waveforms, while the last is a particular technique for retrieving the bullet track that could use the radar echo information from any of the three waveform options.

Continuous wave radar option: in this option the transmitter and receiver both operate continuously. The transmitter and receiver antennas are separated and the receiver frequency is offset from the transmitter frequency, so that the receiver is not overloaded with power coupled directly from the transmit antenna to the receiver. Since the received signal is Doppler shifted by as much as about $f_d = 2v_{\mathrm{radial}}/\lambda \sim 200$ kHz (for a 35 GHz radar), this is a practical arrangement. In this mode Doppler shift and hence radial velocity information is acquired directly from the echo signal received at three or more receive patch antennas as shown in Figure 10. In addition information can be derived by combining coherently the signals from multiple receiving antenna patches as discussed below.

The primary information available from such a system consists of several time series of radial velocity from antenna patches at different locations on the helmet in Figure 10. Allen and Stoughton [2] have analyzed the retrieval of bullet trajectory information from a trio of radars operating in CW mode. For a single radar the Doppler time history yields the impact parameter (or distance of closest approach b) and the time of closest approach t. Using a simple retrieval algorithm involving the separate fits of bullet trajectories for each of three radar locations they derive an azimuth for the source of bullet. They find an angular error of less than 2° for a trio of 5 GHz radars separated by about a foot and trajectories that passed within 10 m of the radar. For this retrieval scheme the error variance scales as the ratio of wavelength to separation squared. Hence, for our 35 GHz radar and a receiver antenna spacing of about 10 cm we would expect similar or better estimation of the azimuth of the bullet track.

As pointed out by the above authors, one anticipates better trajectory estimation from applying a least squares or other fitting procedure to the Doppler data from all three radars used simultaneously. Further improvement can be anticipated by using data from more than three radars, i.e. transmitter and receiver patch antenna pairs. As discussed below one can use an inverse SAR approach that would fit a trajectory to the entire face history of the bullet radar echoes.

In Figure 10 we show two circular bands of radar receive antennas with six antennas each, wrapped around the helmet. Since we receive signal phase for each of the antennas, we can do some manipulation of the antenna pattern of various combinations of the multiple antennas. For example, this capability could be used to form interference patterns of peaks and nulls spaced at 1/D, steer the interference pattern and form the complementary pattern, replacing peaks with nulls. Although we have not done a thorough analysis, we anticipate that the bullet trajectory can be located in angle in the vertical plane passing through the radar location and the point of closest approach.

This information added to the Doppler time histories should allow at least a crude in estimate of the origin of the bullet trajectory in elevation angle.

Potential issues that arise from this approach are echoes from a burst of bullets, background noise radio noise level and location of the bullet trajectories origin in elevation angle. It is likely that sniper fire in urban warfare will involve automatic fire as well as single shots. For rates of fire of 600 to 800 rounds/min we expect 60 to 80 m between bullets. Because of the limited range of the radar we would not expect echo signals from two bullets, shot from the same weapon, to interfere significantly. In the calculations above and below we have assumed that the background noise level is composed of the thermal noise radiated by the ground ($\sim$ 300 °K) and the receiver front-end amplifier noise ($\sim$ 200 °K). This level is a minimum and may be higher in an urban area. The radar is also vulnerable to jamming in its simplest form, but could be rather easily protected against narrow band jammers by frequency agile operation or random frequency hopping.

FM-CW Radar operation: The CW mode radar waveform discussed above does not provide range information (although range can be determined indirectly by fitting Doppler versus time). A small modification allows range information to be retrieved. In FM-CW mode the radar is continuously transmitting and receiving, but the frequency of the radar is varied, for example a linear-ramp change in frequency of Δf in time τ, first upward and then downward in transmit frequency. By comparing the echo signal frequency with the transmit frequency for both the upward and downward sweeps one can retrieve both radial velocity and range with resolutions of $\delta V_{\text{radial}} \sim (\lambda/2\tau)$ and $\delta r \sim (c/4\Delta f)$ respectively (Skolnik, 1980).

To compare the frequencies of the transmitted and received signals we simply mix the received echo signal with a low amplitude sample of the transmit signal. The difference between the two, i.e. the beat frequency f_b, is given by the sum of a term f_r due to the time delay of the echo signal, and

a term f_d due to the Doppler shift of the echo signal:

$$f_b = f_r + f_d = (2\,R\Delta f)/c\tau \ \pm (2V)/\lambda\,, \tag{10}$$

where R is the range of the target, Δf is the frequency change of the ramp (or chirp) in frequency over time τ, V is the target's radial speed and λ the radar wavelength. V is positive for a target approaching the radar.

Since FM-CW radar yields range information, the issue of range ambiguities arises and influences the selection of the upramp-downramp waveform as shown in the figure below. If we use only an upramp waveform it is easy

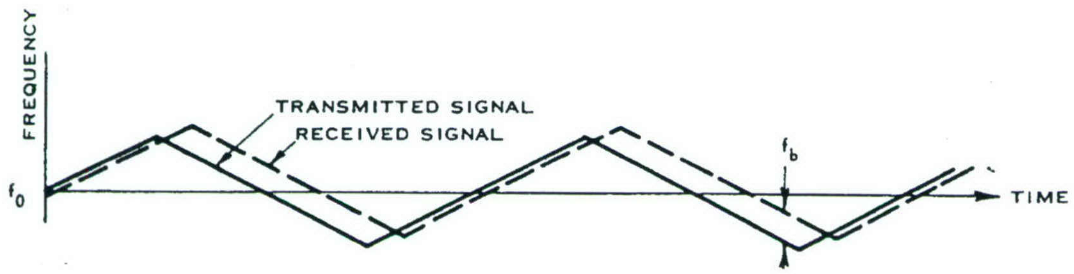

Figure 12: Upramp-downramp chirp waveform, as transmitted and received (after [23]).

to see from (2) that the range and radial velocity of the target both determine the observed beat frequency f_b. However, if we obtain a beat frequency for both the up and down ramp waveforms we note that the Doppler term f_d changes sign during the down ramp due to Δf being negative instead of positive as shown in the figure above. Thus, for the up-ramp we have $f_{bu} = f_r - f_d$ and for the down-ramp $f_{bd} = f_r + f_d$. We can remove the range-velocity ambiguity by adding f_{bu} and f_{bd} to obtain the range term and taking the difference between f_{bu} and f_{bd} to obtain the radial velocity term. If we used only the up-ramp the range-velocity ambiguity would still remain, but could also be removed by other methods, such as the interrupted CW or chirp-range-Doppler approach discussed below.

We have done a straightforward calculation to estimate the performance of a 35 GHz FM-CW radar for bullet tracking. The radar parameters of the calculation are summarized as follows:

Frequency = 35 GHz
Power = 0.1 W in Standby and 5 W in Alert
Δf = 20 MHz (frequency change of FM-CW waveform)
τ = 1 ms
Transmit antenna gain = 3 dB
Receive antenna gain = 38 dB (full phased array)
RCS = 6.5×10^{-5} m^2 average or 4×10^{-4} m^2 (end on)
T_{sys} = system noise temperature = 500 K
L_{sys} = system losses = 3 dB

The standby mode uses a 50 pulse coherent average to detect bullets at longer ranges using low power to reduce battery demands. The alert mode increased power by a factor of 50 to allow sufficient SNR to track a bullet and sample its trajectory every 1 ms (every meter or better) and prevent smearing of the Doppler measurements. The transmit antenna is in the crown of the helmet (Figure 11) and forms a roughly omni directional pattern over the upper hemisphere with slightly more gain in the horizontal plane and less directly overhead. The receive antenna is fully functional phased array that allows much more gain by being able to scan a large coverage area with high gain electronically using digital beamforming. The RCS of the bullet at 35 GHz is shown in Figure 9 and we have used the end-on RCS = -34 dBsm (dB relative to a square meter) for the standby mode since the bullet will be coming nearly directly toward the radar. For the alert mode we used a more average number for the bullet cross section, namely -42 dBsm. For the system noise temperature we used that of the Earth ($\sim$ 300 K) plus a 200 K allowance for receiver noise, making a total of 500 K. We also allow a factor 2 loss for cables, etc.

Using these radar parameters we can estimate the range for a given signal to noise ratio (SNR) as shown in Figure 13 below. We see that the radar can detect bullets at SNR $\sim$ 14 dB at a maximum range of about 70 m. For Gaussian noise this implies a probability of detection of 0.999 with a false alarm rate of 5×10^{-4} or one about every two minutes. Since the alert mode

can verify the detection, false alarms at this rate should neither be disconcerting to the operator nor use excessive power.

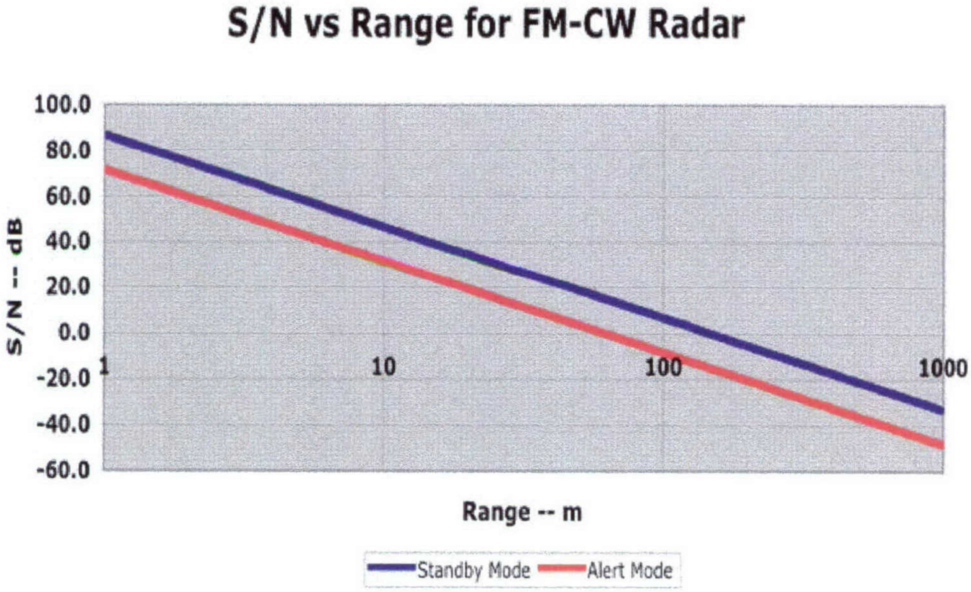

Figure 13: Signal to noise performance for an FM-CW radar operating at 35 GHz. The standby curve is for reduced power, but a coherent average over 50 ms to detect bullets at increased range. The alert curve uses a 50 times increase in power to achieve greater accuracy, but is only activated when a bullet is detected in standby mode.

The FM-CW waveform provides range and radial velocity information. The range resolution $\delta r \sim c/(2\Delta f)$ and the radial velocity resolution is $\delta v_{\text{radial}} \sim \lambda/(2\tau)$. From the parameters above in alert mode we find $\delta r \sim 1.5$ m and $\delta v_{\text{radial}} \sim 4\ \text{ms}^{-1}$. In standby mode the averaging over some 50 ms means that the range information can be no better than about 40 m and the radial velocity information will be smeared out due to the changing radial velocity of the bullet as it approaches.

Since we have chosen a full phased array system, the bullet direction can be defined rather well by the phased array antenna. The angular beam width of the antenna of Figure 11 is about 3° (or 6 m at 100 m range) in the horizontal plane and similarly for the vertical plane. Here we have taken each elemental patch in the phased array to have a beam width of 60°. Thus, we

can located the source of the bullet to within about 3° in angle when in alert mode and somewhat less accurately in standby mode due to the averaging for 50 ms.

The directional information from the phased array coupled with the range and radial speed information in alert mode provide a firm basis for tracking a bullet that passes within a few tens of meters of the radar and locating the origin of the trajectory to within 3° or better.

Clearly there are a lot of issues that are properly resolved by design trade studies beyond the scope of this brief look at the problem.

Pulse Doppler operation: Another waveform option is pulse Doppler. In this option the radar is operated as a pulse radar with pulse-to-pulse coherence. One thus collects a time series of phase coherent echoes from a target in one or more range and azimuth resolution cells (for example, see [28]). The time series of echo phase can be Fourier transformed to produce the Doppler shift of the target echo.

The advantages of pulse Doppler operation are collection of range information, flexibility in use of the information collected and ease of applying moving target indicator (MTI) techniques. The disadvantages are greater complexity in signal processing, typically lower duty cycle (fraction of the time that the radar is transmitting) than CW or FM-CW radars and hence typically lower SNR for the same peak transmit power levels, dealing with range ambiguities if high pulse repletion rates are used, and higher peak power levels than CW or FM-CW waveforms. Because the relative advantage appears to lie with CW and FM-CW waveforms we did not assess pulse Doppler in this brief study. It should certainly be considered in a more comprehensive design process.

For many pulse-Doppler radars an interrupted FM-CW (IFMCW) waveform is used for each pulse so that more energy can be put into the pulse for a given peak transmit power. Upon reception the FMCW or chirp pulse can be compressed (by using a filter with a time delay that is proportional

to received frequency) to yield a very short pulse with high range resolution.

Among the design constraints on this type of wave form is the range-Doppler ambiguity of a single up-ramp or down-ramp pulse (see [18, ch. 7] for a discussion). We see from Equation 10 above that a bullet with a radial velocity of 400 m/s at a range of 10 m would produce the same f_b response as a stationary ($V = 0$) target, such as a building, at a range of $\sim 700\,\mathrm{m}$, although weakened by being at a further range. The danger is that the large building at a further range can produce a stronger echo than a small bullet at a shorter range. To avoid this situation we need to increase (τ/f) as indicated by Equation 10. Another constraint is the need to allow enough time between chirps to receive echoes from the maximum range for which targets lie within the line of sight of the radar, probably about 20 km. This implies a maximum pulse rate of $(c/2R_{\max})$ or $\sim$ 7500 pulse per second. During this time the radar is not transmitting and thus signal to noise ratio is reduced. A further constraint is the need to make the pulses close enough together to resolve the maximum Doppler shift to be encountered; $\sim$ 400,000 samples (pulses) per second are needed. Clearly there is a conflict here. It can be resolved by using coded pulses, but at the cost of increasing the complexity of the radar.

Inverse SAR methods: In a typical synthetic aperture radar (SAR) a moving platform is used to synthesize a large antenna aperture so that very high angular, e.g. azimuth, resolution can be obtained from a small antenna. In inverse SAR the target moves instead of the radar platform. It is the relative motion of the target and radar that is important. The phase (Φ) of the radar echo is controlled by the product of the radar wavenumber ($k = 2\pi/\lambda$) and the range R from radar to target, namely $\Phi = 2kR$). The Doppler frequency shift f_d is the time derivative of Φ, $f_d = d\Phi/dt$. Thus, as the target moves, changes in range are linearly related to changes in Φ and to the integral of the Doppler shift f_d. CW, FM-CW and pulse Doppler waveforms can all collect a time history of Φ. Pulse Doppler is the most direct.

Inverse SAR is the technique of using the phase time history of radar echoes to retrieve information about the target. The most well known applications are to imaging of moving airplanes, ships and space objects. The rotation of the target is the most important motion in imaging such as target. Wehner [28, Ch. 7] gives a useful summary of the technique. For bullet tracking one wants to retrieve the trajectory of the target from the phase history. For the bullet tracking application one develops a predicted target phase history for each possible bullet track and then compares the observed phase history with the predictions to find the set of predictions that most closely match the observed phase history. For a set of straight-line bullet tracks this is a relatively simple optimization problem. However, for single radar with a non-directional antenna there are a number of solutions that all have the same phase history, namely all the bullet tracks passing the radar at the same distance of closest approach. Thus, information from multiple receive antennas would be needed to resolve some of the ambiguities and determine a useful bullet track. This is problem is discussed above in connection with the CW radar option and the simple helmet antenna of Figure 9. Use of inverse SAR techniques in connection with all the radar options appears to be best approach to determining a bullet track although computational requirements might be a concern.

Hardware Implementation of a Bullet Tracking Radar for a single soldier: The goals of our hardware implementation are to have the helmet antenna be significantly less than a pound and the electronics and battery be similar to a cell phone. Below we discuss the technology through which to accomplish these goals. Three subsystems are discussed below, namely, antenna, electronics and battery.

The antenna is likely the most difficult part of the radar to implement within the goals above. To populate the lower tiers of the helmet with patch antennas having dimensions of half a wavelength or about 0.5 cm on a side for 35 GHz operation requires about 7000 patches to cover the 1260 cm^2 area of the lower tiers in Figures 10 & 11. It is clear that this would be a man-

ufacturing challenge and probably not currently feasible if each patch were an independent receive channel. However, this number can be significantly reduced by using a thinned array.

For the antennas of the simple type of Figure 10, the demands on number of elements is less stressing. The goal of the simple antenna is to use patches to produce a broad antenna pattern so that the target can be observed as it passes by the radar. In this implementation a large number of patches would be arrayed with fixed phasing, such that the desired broad antenna beam is produced. In the illustration of Figure 10 there are 12 separate receive channels connected to the 12 antenna segments. These 12 segments would need some 600 patch elements each. The ease of fabrication of patch antennas makes this approach possible. However, it may be that the fragmented aperture approach would serve the purpose better as illustrated in Figure 14 below. These antennas are a patchwork of discrete conducting

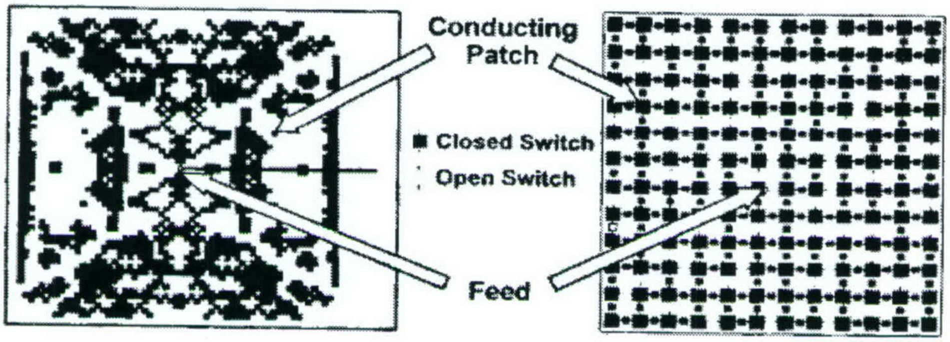

Figure 14: Fragmented aperture antenna concept. The array on the left is a fixed fragmented array and the one on the right is configured by setting switches to form the desired fragmented patchwork pattern. (After [20]).

and dielectric elements distributed over an aperture and can be assembled optimized desired characteristics. The design process uses genetic algorithms in conjunction with finite difference time domain (FDTD) techniques to determine the radiation pattern of each particular configuration considered. A large number of iterations are employed to reach an arrangement of the patchwork that produces the desired antenna pattern. They have many of the advantages of the patch antennas described above.

A full phased array as discussed in connection with the FM-CW radar above would require the full 7000 patches and the corresponding 7000 receiver channels. This would be a significant fabrication challenge. A feasible number of receive channels would probably need to be less than 1000. This could be accomplished by thinning the array by about a factor of 10 and using sub arrays with fixed phasing. The resulting array would probably perform satisfactorily, but would involve more a complex design process and testing.

A more practical approach would be to postpone immediate consideration of the full phased array approach of Figure 10, awaiting development of the technology to the point when such an antenna can be implemented on a helmet with robust, low cost, phased array technology. CW, FM-CW or pulse Doppler waveforms can be used with the simple antenna of Figure 9, but the direction finding information of the phased array would be lost and trajectory determination would be done using primarily radial velocity or radial velocity and range information with some supplementary spatial information through the interferometric approach discussed above. Alternatively one could consider approaches somewhere in between the full phased array and the simple antenna.

MMIC (monolithic microwave integrated circuit) electronics are a key technology in the pursuit of a bullet tracking radar for a single soldier. This development over the past 35 years has produced ever more effective and compact microwave circuits. In Figure 15 below are examples of receive and transmit MMIC's that measure less than 2 mm on a side and are less than 1 mm thick. These MMIC's incorporate amplifiers, mixers, oscillators, resonators, etc. on a single chip. It is this technology that makes possible the compact cell phones we use today. They also make possible the bullet tracking radar suggested here.

Weight, power and volume estimates for bullet tracking radar can be made on the basis of the technology discussed above, i.e. patch antennas, MMIC, etc. We will use for our estimate the simple antenna of Figure 9

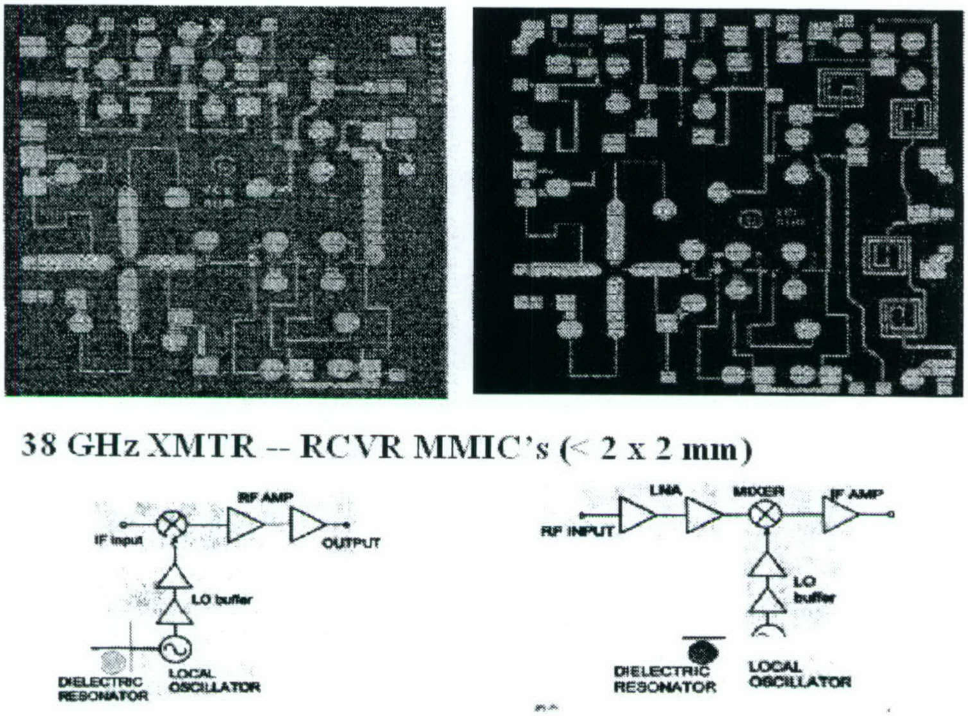

Figure 15: Monolithic Microwave Integrated Circuits (MMIC's) for 38 GHz transmitter (left) and receiver (right). The schematic diagrams are below the photos of the MMIC devices. Note that each is about 2×2 mm in area and less than 1 mm thick; so there is no difficulty incorporating a large number of these devices into a helmet antenna. (After Waterhouse).

above, the MMIC transmitter technology (Figure 15) and associated signal processing and display circuits. For power we suggest a Li-ion battery with very high energy density as well as high peak power capacity for the alert mode of operation. Li-ions are also rechargeable. These batteries are proven, safe technology and are used in modern cell phones. The power, weight and volume estimates are given in Table 4 below.

For the antenna we estimated a layer of dielectric material, the density of plastic and 1 mm thick, covered by a layer of copper conductor 0.2 mm thick for the antenna patches. The total area covered was taken to be the hemispherical area of the helmet. The resulting weight estimate is very conservative and probable an over estimate by a few 10's of percent, but this could be allocated to cables between antennas and electronics. We have

allocated no power specifically to the antenna, but have allowed for a conservative 3 dB loss in antenna and cables. For the electronics we allow for the transmit-receive MMICs (one per antenna segment), i.e. 12 for the antenna of Figure 9. We also allow for a multichip module for data processing making a total of 4 oz that is mostly packaging. We estimate the power required by all the electronics to be about 10 times the transmit power of 1 W continuous. The time in the alert mode has negligible impact since the unit is on alert for less than a 1 s at a time. This allows for about 5 hours of operation without recharging or changing batteries as discussed below. The volume of the electronics is estimated at 2 in^3.

We have not included power, weight or volume for a display for the radar output. We assume that the sniper location would be displayed on an existing visible or IR imaging system.

Table 4: Power, Weight and Volume Estimates

Function	**Power/ Energy**	**Weight**	**Volume**
Antenna	0 W	12 oz	9 in^3
Electronics	1 W	4 oz	2 in^3
Battery	5 Whr	2 oz	1 in^3
Total	1 W	18 oz	12 in^3

A sanity check can be had by comparing these estimates with a modern cell phone. The power, weight, and volume are comparable with the cell phone with two exceptions, the much more elaborate antenna and the transmitter for the radar being on continuously. The radar in alert mode is like a cell phone while transmitting.

Conclusions & Recommendations: Considering recent advances in "printed antennas" and monolithic microwave integrated circuits we developed a notional design for a single soldier bullet tracking radar. We conclude that such a system could be built and deployed under the requirements that it provide the origin of the bullet track with useful accuracy, while not unduly

burdening the soldier by way of weight or volume. The resulting notional design results in a system that has an estimated weight of about a pound including battery, but not display; and an operational duration of about 5 hours on a single battery charge. We have done only a feasibility analysis of bullet radar operation, *i.e.* obtaining the right kind of data to track bullets. Accuracy has been assessed by [2] and from their analysis we project an accuracy of a few degrees in azimuth. We do not have an estimate for accuracy in the elevation direction, but preliminary consideration suggests that it will be useful.

We recommend the following:

1. Do a comprehensive preliminary design of a single-soldier bullet tracking radar, based on the design requirements discussed here, developing alternative concepts, evaluating them and defining a baseline design to pursue to construction and test if the preliminary results justify further effort.

2. Conformal antennas, such as the patch or fragmented types above, applied to a soldier's helmet offer opportunities to increase antenna performance and perhaps reduce weight while making the antenna less obtrusive. In addition to bullet tracking radars such antennas appear to be a good match with the personal radios discussed in section 2 of this report. We recommend further investigation, design and development of such antennas for helmet use.

6 SEEING THROUGH WALLS

Two of the most pressing problems of urban warfare are seeing through walls and precision location of the individual soldier. We make a few suggestions in each area, in some cases relating the two issues. Some of the suggestions are updates of previous JASON suggestions [5, 12]. We report on a commercially-available product for precision indoor geolocation, which represents commercialization of DARPA-sponsored research in the area of urban warfare. We point out (as discussed in §3) that RF emissions used for see-through-the-walls SAR are also useful for geolocation in ways other than conventional pseudolites.

Penetration of walls by various means is important in two contexts. First, one wishes to view the interior of a building to see if there are humans inside, and if possible to discriminate among friendly forces, hostile forces, and innocent civilians. Second, one wishes to penetrate building walls, both interior and exterior, with signals that might enable precision location. There are several scenarios for seeing through walls. In some cases the one doing the seeing does not want to be detected (unobtrusive seeing), but in other cases this may be relatively unimportant, provided that hostile detection of the viewing soldier does not compromise that soldier's safety (obtrusive seeing). In some cases the issue is to look into a building from the outside; in others, it is to see from one room to another or to map out the interior of a building already entered.

There is already a considerable amount of work on seeing through walls with various types of radar. In the Army Sensor Through the Wall (STTW) program, tests were recently conducted on six prototype radar technologies, including the ultrawide band technology discussed in Sec. 6.2. One important conclusion from these tests is that a frequency around 2 GHz provides "acceptable attenuation and resolution for through wall sensor applications. A frequency of 2 GHHz will also allow for antenna elements small enough for use in a hand held configuration."[9]. The essentially commercialized radar

technology of Sec. 6.2 has a center frequency of 1.5 GHz, and we believe these remarks would apply to it as well.

6.1 Obtrusive Seeing Through Walls

Here is a suggestion for seeing through walls when the fact of observation is unimportant. A special round is used that can be fired from an M16 in the same way as a grenade is launched. With the M16, grenades of 40 mm diameter are launched through a special demountable barrel and trigger assembly. Consider a cartridge of this size which consists of a smaller-bore front end and a rear end which is essentially a toggle bolt assembly in the folded position. Toggle bolts are used in hollow walls, made of (a combination of) plaster, wood, and dry-wall, to insert and hold a bolt with access only to the front side of the wall. The toggle bolt assembly has several metal slats that are held in place initially; when they are freed a spring or other mechanism spreads them out to a diameter several times that of the bolt hole, thereby keeping the rear end of the bolt from coming through the hole drilled to hold the bolt. The special grenade cartridge is long enough for the front end to penetrate through standard wall thicknesses when the rear end is stopped from penetrating by the toggle assembly; the cartridge contains a sensor device of some sort, and a way of communicating what it senses back to the soldier firing the cartridge. Most likely this is a simple wire, since the cartridge will be fired from a distance of tens of meters at most.

The sensor encounters considerable deceleration as it enters the wall. The value a of the deceleration depends on the initial velocity v and effective wall thickness s. The effective wall thickness may be the actual wall thickness, or a thickness set by spring constants involved in setting the toggle assembly. The minimum deceleration is that for uniform deceleration, in which case the usual formula gives

$$a = \frac{v^2}{2s}. \tag{11}$$

What velocity is needed depends on the wall thickness and yield strength Y; given a cartridge mass density of ρ, the minimum velocity for any penetration is

$$v = \sqrt{\frac{2Y}{\rho}}. \tag{12}$$

For materials other than steel or concrete, such as wood and plaster, the velocity v need not exceed 100 m/s, in all likelihood, corresponding to an acceleration of 10^4 g or more. It does not seem an insurmountable problem to construct solid-state electronics capable of such accelerations, and in past years numerous groups have developed this type of electronics for impact fuzes and smart munitions, whether launched from conventional artillery, rail guns, or gas guns. A high-g electro-optical system can also be constructed, using a focal plane with a lenslet array or simply no lens at all. In the latter case, one might merely detect motion (as with household passive IR detectors). Or the sensor could be acoustic.

6.2 Unobtrusive Seeing

We discuss a new application of L-band ultra-wide-band (UWB) technology that was developed under DARPA initiatives some time ago for urban warfare. This technology has been commercialized; we will discuss the specific products available (or soon to be available) from Multispectral Solutions, Inc [11]. Our discussion of these commercial products is not intended as an endorsement, but simply as an example of what is now available. Other firms [7] produce and sell UWB products for various radar applications. The advantages of UWB in both the applications we envisage and those of Multispectral Solutions are: Increased resistance to (indoor) multipath and precise (0.3 m or so) location solutions. Multispectral Solutions produces the PAL650, a UWB RF tag and receiver combination used for tracking and locating valu-

[7] For example, Intelligent Automation, Inc is teaming with Time Domain Corporation, maker of UWB ASIC chips, in a DoD-funded UWB radar project.

able assets in buildings [11]. The tag itself is very small and low-powered, as befits a tag, and is not what we are looking for.

Multispectral is working on a somewhat larger and more powerful version which apparently is not yet quite off-the-shelf [10]. There is no Multispectral model number for this system, so we will invent the acronym UWBPL (UWB Precision Location). The UWBPL hardware consists of receivers and transmitters centered at 1.5 GHz, with a 400 MHz bandwidth. Peak power is 4 W for 2.5 nanosec pulses at a 100 Hz rate. (Clearly, the average power is very much lower.)

The original Multispectral application of precision location over ranges of 0.1–2 km will be described in the next section. For now, we are interested in the proposition that the Multispectral UWB L-band lightweight transmitters and receivers could well form a foundation for a SAR system capable of seeing inside most buildings, with little or even no modification. The SAR transmitters are light enough and consume so little power that they could be mounted on small UAVs such as the Silver Fox with about a 2 kg payload and 50 W of payload power. Smaller SARs, such as Dragon Eye, probably are too small for the antenna, which has to be about 1 m in size (which is much larger than the simple half-wave dipoles used in the Multispectral application). Of course, the SAR radiation has to penetrate buildings. Buildings made of dry wood, brick, or dry concrete should be penetrable. In these materials the two-way absorption constant (which depends strongly on water content) might be of the order of 0.01 cm^{-1}, and the two-way transmission due to reflection loss in air might be about 0.7. With a 400 MHz bandwidth the SAR range resolution would be about 40 cm, and at a range R of 1 km, UAV velocity v of 30 m/s, and coherent processing time T_I of 5 s, the cross-range resolution Δx would be

$$\Delta x = \frac{\lambda R}{2vT_I} \simeq 70\,\mathrm{cm}. \tag{13}$$

Resolution in this range should be enough to detect the presence, but clearly not the identity, of non-moving humans. If humans move, there are two problems. The first is that if a person moves a few meters in the five seconds

of processing time, the image will be blurred, contrast will be lost, and the human may go undetected. The second is that even if the human is detected his position will be offset in azimuth by perhaps a few meters.

The original Multispectral pulse repetition frequency (PRF) of 100 Hz is probably suitable for a SAR, although it seems evident that it can be increased if need be. We must require that the Nyquist criterion for Doppler processing is satisfied:

$$PRF > \frac{4v}{D} \tag{14}$$

where D is the aperture size. The Nyquist criterion can be interpreted as the statement that the number of pixels in a cross-range swath is no more than 1/2 the total number of range pulses. Given our parameters, there can be no more than 250 pixels, of 0.7 m size, for a scene width of 175 m. This should be adequate to encompass almost any building. Equating a PRF of 100 Hz to $4v/D$ yields an aperture of 1.2 m; we will round this down to 1 m for the present exercise. This requirement on D is halved if the PRF is doubled. For completeness, we note that the inequality for no range ambiguity is very amply satisfied.

It will be necessary, for the coherent integration of range pulses that is inherent to SAR, that the pulses be accurately controlled over the coherent integration time. In particular, the pulse frequency spectrum must be known and controllable down to a fraction of a Hz, in order to process the SAR Doppler information. And, for purposes such as geolocation or even communication, some ability to transmit and receive coded pulses will also be needed. We have no idea whether such functions are easily incorporated into commercial technology such as that of Multispectral Solutions, but it is not a difficult thing to do in principle.

The final issue we discuss is the signal-to-noise ratio (SNR). We estimate this under the assumption that the pulse generator can generate identical pulses time after time and that the Multispectral system is equippped with a suitable local oscillator. Then, with all parameters in the SNR as given

above plus the assumption of a -10 dBsm target yields about 20 dB, for the Multispectral peak power of 4 W and pulse repetition frequency of 100 Hz. This must be reduced by the reflection and transmission loss factors mentioned above, as well as by system inefficiencies beyond thermal noise. If at the end of the day this SNR is not enough, the simplest way to improve it is by increasing the power or the PRF or both.

7 CONCLUSIONS AND RECOMMENDATIONS

This report has focused on better sensors for Marine infantrymen in urban terrain. It is clear that Marines so engaged have important needs other than sensors: more extensive training and vehicles specialized for urban areas, for example. Within the scope of our study, however, we find that the most immediate need is better communication at the squad level: ideally a radio on every rifleman. Whether a radio constitutes a sensor is a moot point, but radios are certainly means of acquiring information, and to the extent that restricted lines of sight require sensors to be networked, radio will be essential to their effectiveness.

Recommendation #1: *The Personal Role Radio or equivalent near-term solution should be fielded quickly, and every rifleman should be equipped with one and trained in its use.*

Notwithstanding the above, the PRR's lack of encryption and especially its lack of a data channel are serious drawbacks. These two capabilities should go together: with proper training and discipline, we see no reason that an unencrypted, short-range, push-to-talk voice channel should compromise the squad any more than natural speech as presently used in urban combat. But if sensors are to communicate soldier's locations and other vital data automatically, the data channel needs to be encrypted. Therefore,

Recommendation #2: *A successor to the PRR should be found or developed to provide a secure data channel.*

We see no fundamental technological impediments to such a radio. Experience has shown, however, that even technically straightforward development and acquisition projects can be delayed by multiplication of military requirements, so that the final product lags behind commercial technology. There is no general solution to this problem, but in the present case, we suggest that GSM cellphones and commercially available mobile base stations

might be a near-term way to meet our second recommendation.

Finding one's location in urban terrain presents special challenges. GPS signals do not propagate as well as they do in open terrain, and greater precision is needed. On the other hand, the area of operations is usually smaller. Also, the more closely textured and regular geometry of artificial structures presents better opportunities for navigating by landmarks. We find that some form of RF will remain the most practical mode of navigation for at least the near future, and that the difficult propagation environment can be overcome by increasing the received RF power—which is best done not by increasing the transmitted power but by deploying beacons at much closer range than earth orbit. The standard GPS signal is so weak that there is more than enough headroom so that similarly-powered transmitters at ranges of order a kilometer should be able to be received even within buildings. Ultra-wide-band waveforms show promise for dealing with multipath. Among various options for RF beacons, we have discussed not only GPS pseudolites but also transponder systems and synthetic aperture radars.

Recommendation # 3: *Short-range RF pseudolites or other beacons deployed on tall structures, UAVs, or other vehicles, should be studied intensively for navigation in urban areas and even inside buildings.*

We note, however, that precise inertial measurement units, imaging sensors, and processors are evolving rapidly towards smaller sizes and lower powers, and that some combination of these devices might provide a useful alternative or supplement to RF navigation in the longer term.

For all of their promise, digital maps have not yet supplanted paper ones at the squad level. Paper maps have the great advantages that they are easily stowed, easily marked up, and require no power, but they require skill and close attention to interpret. Before digital maps can be useful in combat at the squad level, they will need a much more robust, more compact, and less distracting interface than a laptop: probably a heads-up display, though

some of the study members believe that digital paper shows promise.

Recommendation #4: *Light-weight, low-power devices need to be developed for displaying map data in combat.*

It would obviously be very useful for the soldier to see his own and his comrades' positions superimposed on the map display.

As to the content of digital maps, we find that a good deal of manual effort is still required to produce them. It is hard to avoid manual annotation of the functional or cultural significance of structures, but geometric modelling could be more automatic if better 3D data were routinely available—stereo-optical, imaging radar, or lidar, for example—and would allow the local scene to be computed and displayed as it should appear from ground level. (At the moment, for lack of 3D data, building heights are often estimated by hand by counting windows.) This would be advantageous not only in navigation but also in designating targets precisely for indirect fire. We forbear to make specific recommendations along these lines because we did not study mapping methods in detail. However, since commercial satellites now offer imagery at 0.6-meter resolution,

Recommendation #5: *One should take advantage of commercial sources to image cities of interest at reasonably frequent intervals: every six months or better.*

This would allow more complete and up-to-date 3D information. It might also allow one to learn something of the internal architecture of buildings while they are under construction, although for that purpose, the needed cadence might be still more rapid.

Recommendation #6: *Users should be able to add their own temporary annotations to their digital maps. There should also be clear and user-friendly protocols for reporting errors and updates to the primary mapmakers, and for validating the information reported.*

The unaided Marine cannot easily determine the point of origin of a

sniper's supersonic round. Although man-wearable counter-sniper systems have been developed to the prototype stage, none has been fielded. This report has considered passive acoustic, passive optical, active acoustic, and active electromagnetic bullet-tracking systems. For the near term at least, the passive systems show the greatest promise because they could be built from readily available, lightweight, low-power commercial devices. In principle, both could designate the origin of a bullet track based on data collected by sensors on an individual soldier, especially if the soldier in question is the sniper's intended target. Passive acoustic systems could, however, benefit from coherent processing of shock arrival times at several soldiers communicated *via* a low-bandwidth data channel. Optical detection schemes benefit less from networking, but in the unfortunate event that the sniper disables his target, the sniper's position should be communicated to the wounded soldier's comrades. Active acoustic systems, though feasible and elegant in principle, are likely to require too much power. Man-wearable high-frequency radar systems appear feasible at acceptable power and weight and would probably offer the best single-soldier performance, but they would probably be challenging and expensive to implement compared to the passive systems. Therefore,

Recommendation #7: *A wearable bullet-tracking system based on passive acoustic, optical or IR sensors should be developed and deployed for localizing snipers; even a modest level of performance would be a great improvement over the unaided human ear and nervous system. The feasibility of wearable radar systems should be studied for the longer term.*

The JASON study was not able to gather much information about through-wall systems, so our recommendations in this area are appropriately tentative. As we see it, there are at least two primary goals of a through-wall sensor: (1) to sense people or weapons in a neighboring room; (2) to map the internal structure of buildings before entering them. For the first purpose, an option worthy of study is a specially designed round (launchable from an M16 perhaps) with a retaining toggle bolt at the back end and a

hardened sensor at the front (*e.g.* electro-optical imager, motion sensor, or microphone), especially if this round is used on relatively soft interior walls. The second goal requires a greater standoff and a wider view; it is hard to see any reasonable alternative to radar. The frequencies needed for effective wall penetration are low enough (1-2 GHz) that acceptable resolution requires a large real or synthetic aperture. This consideration, together with the power required for effective penetration of exterior walls, argues for a vehicle-borne rather than man-portable system. We suggest a study, ideally with some experimental data, of the feasibility of mapping the internal structure of buildings at meter-scale resolution from outside, but at relatively close range (a few hundred meters or less) using a wide-band low-frequency SAR or similar system on an aerial or ground vehicle. Simple estimates suggest that a usable electromagnetic return can be obtained if frequencies in the 1-2 GHz range are used, but the signal processing presents special challenges because of multipath.

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A Acronyms Used in this Report

Acronym	Translation
CETO	Center for Emerging Threats and Opportunities
COTS	Commercial Off the Shelf
FRS	Family Radio Service
GMRS	General Mobile Radio Service
GPS	Global Positioning System
IMU	Inertial Measurement Unit
ITU	International Telecommunication Union
INS	Inertial Navigation System
IR	Infrared
ISR	Intelligence, Surveillance, & Reconnaissance
JASON	—
MMIC	Monolithic Microwave Integrated Circuit
MOUT	Military Operations in Urban Terrain
OIF	Operation Iraqi Freedom
ONR	Office of Naval Research
PRF	Pulse Repetion Frequency
PRR	Personal Role Radio
PTT	Push To Talk
POC	Point of Contact
RF	Radio-Frequency
SAR	Synthetic Aperture Radar
UAV	Unmanned Aerial Vehicle
USMC	United States Marine Corps
UTP	Urban Tactical Planner
UWB	Ultra Wide Band

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